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Dissertation

Effects of Variations in Moisture Content on Certain Properties of a Soil and on the Growth of Wheat

BY

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A THESIS

PRESENTED TO THE FACULTY OF THE GRADUATE SCHOOL OF CORNELL UNIVERSITY FOR THE DEGREE

OF

DOCTOR OF PHILOSOPHY

ITHACA, NEW YORK
1914

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EFFECTS OF VARIATIONS IN MOISTURE CONTENT ON CERTAIN PROPERTIES OF A SOIL AND ON THE GROWTH OF WHEAT

FRANKLIN S. HARRIS

(*Received for publication June 25, 1914*)

INTRODUCTION

Moisture is probably the most important single factor affecting plant growth, and it is certainly a powerful agent in influencing the chemical, physical, and biological changes going on in the soil. The fact that the amount of moisture in the field is so variable and so difficult to control, has always made this factor a troublesome one in experiments with soils and crops. Often, when it has been desired to determine the effects of a certain treatment, these effects have been so completely overshadowed by unavoidable changes in the amount of moisture that the results have been valueless.

A practical examination usually shows that in many agricultural sections the availability of moisture is the chief problem confronting the tillers of the soil. In some regions the total annual rainfall is barely sufficient for plant growth. There are other regions where the rainfall would be sufficient to meet the needs of crops if it were properly distributed or if the crop growth could be adjusted to use the precipitation most economically. There are also hundreds of millions of acres of good agricultural soil in regions where the rainfall is just below the amount necessary to make crop-raising profitable with present methods. Most of this land might become productive if the efficiency of the scant supply of moisture were raised to the optimum. Even in regions where there is sufficient precipitation to meet all crop requirements the question of moisture is important, since an excess affects certain properties of the soil that may determine its fertility. Any facts, therefore, that will throw light on the intimate relations between moisture and crops, as well as between moisture and changes going on in the soil, are of much practical importance in helping to solve the great problem of increasing the area of productive soil and making more efficient that which is at present cultivated.

In view of this great practical problem, as well as the theoretical considerations already mentioned, it was thought desirable to conduct a series of experiments under strictly controlled conditions, wherein the soil moisture would be the varying factor, to determine as many of the effects of this factor as possible, both on the soil and on the crop. The fact that these effects are modified by fertilizers and by the period at which moisture is applied to plants, made it desirable to test fertilizers

in connection with the moisture and to change the soil humidity at various periods in the growth of the crops.

The plan was carried out, and the following observations were made on wheat plants under conditions to be later described in detail: (1) growth and morphology of the plants, including length of the periods of growth, tillering, form and structure of the different parts, and general observations during growth; (2) yield and relative quantities of the different parts of the plants; (3) transpiration of the plants, including the total water used, the relation between this and the dry matter produced, the quantity used during various stages of growth, and the relation of transpiration to temperature, sunshine, and humidity of the air; (4) composition of the plants. The effects of some of the same conditions on the following properties of the cropped and the uncropped soils were also studied: volume of the soil, flocculation, nitrates, nitrites, ammonia, total water-soluble salts, number of bacteria, and amount of easily soluble phosphoric acid. Before the experiments themselves are considered, the work of various investigators of the subject will be briefly reviewed.

REVIEW OF LITERATURE

The great importance of water in plant growth and in modifying soil conditions was early recognized by investigators; hence the literature that has accumulated, especially regarding the relationship between crops and moisture, is exceedingly voluminous. It will be necessary, therefore, to limit the number of citations and to omit many important ones.

Much of the literature studied by the author, concerning the effects of moisture on certain of the properties of the soil, is so fragmentary that it will not be presented in great detail. More attention will be given to the literature covering moisture and crop relations. Indeed, it is with this phase of the general subject that most of the author's experiments deal. The work of the various investigators will be brought together under the headings used for the experimental work in the main body of the bulletin.

Relation of moisture to certain properties of the soil

Schlosing pointed out, more than forty years ago, that the quantity of nitrates found in a soil increases with the humidity, when there is not sufficient humidity to wet the soil to the extent that a free passage of air is interfered with; and Warington found later that where there is a great excess of water in the soil, denitrification takes place.

Gain (1895a)[1], in connection with other important work, showed that

[1] Dates in parenthesis refer to bibliography, pages 860 to 868.

soil moisture has a great effect on the action of bacteria. He found that a medium moisture content (about fifty per cent of saturation) is the most favorable for tubercle formation.

King has done considerable work on soluble salts and nitrates, and the relation between them under various climatic and cropping conditions. He found that the ratio of total soluble salts to nitrates varies between 2.14:1 and 9.97:1 under different conditions. The total soluble salts, and especially the nitrates, are higher in fallow than in cropped soils. The crops also seem to take up the nitrates faster than the other soluble salts. These results are summarized in "A Text-book of the Physics of Agriculture," pages 92–107.

Stewart and Greaves (1909) found that on an uncropped soil, to a depth of ten feet, there is more nitric nitrogen in a soil receiving a medium irrigation than in one receiving no irrigation. Immediately after irrigation, however, there is less nitric nitrogen in the surface foot of the irrigated soil than in the surface foot of the non-irrigated soil.

Jensen (1910), in agreement with the work of many other experimenters, found more nitrates in summer-fallowed soil than in soil cropped with wheat or corn.

Buckman (1911) has shown that under dry-farm conditions the formation of nitrates is greater where there is a good supply of soil moisture than where the soil is dry.

Free (1910) has thrown considerable light on the question of flocculation and the way in which it is affected by different soil treatments.

Davis (1911) showed the effect of a number of the soluble salts in modifying the flocculation and other physical properties of the soil.

Ellett and Hill (1913) found that the application of phosphate fertilizer to soils of limestone derivation can be detected by fifth normal nitric acid the year after its application. The addition of fertilizers does not seem to influence the water-soluble phosphoric acid in such soils.

Lyon and Bizzell (1913 b) have clearly shown that the formation of nitrates is influenced by the crop growing on the soil.

Relation of moisture and fertilizers to the growth and morphology of plants

Length of period of growth.— Schroeder (1896) found that the length of the period of growth of barley is prolonged in proportion to the quantity of water available to the plants, and is also affected by the amount of salts contained in the soil. Abbe (1905) and Mayer (1898) both reported experiments wherein the crops matured earlier in dry than in wet soils.

Tinsley and Vernon (1904) found that on an adobe soil in New Mexico excessive irrigation retarded the ripening of grain for a few days.

Prianishnikov (1900), on the other hand, found that the period of vegetation of wheat was somewhat shorter when the moisture was greater.

Von Seelhorst and Krzymowski (1909) found that the way in which moisture affects the date of ripening depends somewhat on the variety of wheat, but is always later with seventy per cent saturation than with more or less water. It must be borne in mind, in considering the various experiments with moisture, that what one investigator calls high moisture another might call medium, or even low. This fact will explain some of the apparent discrepancies between the work of various investigators.

Tillering and miscellaneous observations.— Schroeder (1896) found that the development of adventitious stalks, or tillers, in barley is more pronounced with greater concentration of salts for the same humidity.

Lyon (1907) showed that tillering is favored by a rich soil, and also by cool nights and hot days.

Von Seelhorst (1900), testing the effects of different amounts of moisture on the form of oats and spring wheat, found the following results: With oats the high percentage of water during the early periods of growth increased the number of internodes, and during the period of heading it increased the length and strength of the culm. A high soil-moisture content when the plants were heading considerably lengthened the two upper internodes and the rachis. The number of zigzags in the rachis, as well as the number of spikelets, was increased by a high percentage of water during early growth; while the number of blossoms developed in the spikelets was relatively much greater when the water content of the soil was high at the time of heading than when it was low. The results with wheat were in many respects the same as with oats, but the effect of the water content during the early period of growth was not so marked. The length of the head of wheat depended on the high water content during the early vegetative period. Increasing the soil moisture at the time when the wheat began to head did not increase the number of spikelets, but it was very effective in increasing the number of developed blossoms.

Von Seelhorst and Georgs (1900) found that high soil moisture with high nitrogen fertilizers favors tillering in barley. It also causes the number of internodes to be increased, as well as the length of each internode. The length of heads is likewise affected, being increased by high nitrogen fertilizers and high moisture together, but shortened when high moisture is maintained without the fertilizer.

Preul (1908) found that the length of the wheat culm depends on the moisture content of the soil at the time of sprouting, and that the length of the head depends on the soil moisture during early stages of growth.

Ohlmer (1908) and Meyer (1909) showed that the amount of soil moisture and fertilizers has a great influence on the shape, as well as on the size, of wheat heads.

Eberhardt (1903), as a result of studies with moisture on a large number of plants, concluded that excessive drought results in the dwarfing of the stems, associated with an increased rigidity and diminished length of stems but with an increase in the number of internodes. There was also a reduction in the size of the leaves, an increase in their thickness and in the intensity of color, an increase in hairiness, and an earlier leaf fall. Eberhardt's work included also microscopic studies of structure.

Kolkunov (1905) also has made many histological examinations of plants inured to drought.

Gain (1895b), in his very extensive work on the physiological rôle of water in plants, says that humid conditions augment the number of seeds and fruits produced, while drought decreases inflorescence and number of seeds. He lays great stress on the periods during which plants should receive various degrees of soil humidity.

Hellriegel, and afterwards Wagner (1908), showed that during early stages of development the root growth of plants is proportionately greater that during later stages.

Preul (1908), von Seelhorst and Georgs (1900), Schroeder (1896), Bünger (1908), and Kiesselbach (1910), all brought out the fact that root growth is proportionately greater in a soil low in humidity, or in one low in fertility, than under the opposite conditions.

Polle (1910), studying the effect of fertilizers, moisture, and compacting on the ratio of roots to tops of barley and wheat, found that one gram of roots produces a larger quantity of aboveground parts in both clay and sand when fertilized than when not fertilized, a larger quantity in a moist soil than in a dry soil, and a larger quantity in a compact soil than in a loose soil.

Pfeiffer, Blanck, and Friske (1913), after experimenting for two years with several kinds of soil receiving different quantities of water, concluded that the ratio of grain to total yield decreases as the water supply increases. The nitrogen content of the crop decreases, while the potash, and especially the phosphorus, increases, with increase of water supply.

Von Seelhorst (1911), as a result of the work of fourteen years, found that the soil moisture is capable of influencing the ripening period to such an extent that varietal characters are lost.

Relation of moisture and fertilizers to crop yields

Von Seelhorst (1900) pointed out the importance of a high soil humidity for oats at the time of heading, in increasing the yield of straw and grain. Later von Seelhorst and Krzymowski (1905) showed the effect of high and of low soil moisture, during the various stages in the growth of plants, on the yield of grain and of straw.

Tinsley and Vernon (1904) concluded that wheat will do well, up to the time when the heads fill, in a soil that would be comparatively dry for corn; and that if the soil is kept moist at the time of filling, the yield will be about as good as if the high moisture content had been maintained throughout the season.

Von Seelhorst and Georgs (1900) found an increase in the weight of heads when high moisture accompanied a nitrogen fertilizer; but the ratio of grain to the entire plant decreased with high soil moisture when a nitrogen fertilizer was not applied to soil deficient in nitrogen.

Mayer (1898) concluded, after working for a number of years with rye, wheat, oats, and barley, that, as a rule, the less the moisture, the greater is the relative growth of grain. Bünger also came to the same conclusion.

Widtsoe (1902) found that the percentage weight of heads is greater for heavy irrigations than for light; also that late irrigations are good, for the yield of wheat in particular, and that they are helpful in transferring nutritive materials from the stalks to the heads.

Pulman (1904), working with buckwheat, decided that it is impossible to get a good yield without a high soil humidity at the time when the seed is forming.

Waters and Hess (1896) found with wheat that the largest yield of straw was from plats receiving a complete commercial fertilizer, and especially from those receiving high nitrogen.

Fleischer (1897) observed an almost uniform widening of the ratio between grain and straw with increased nitrogen content of the soil.

Prianishnikov (1900) found, contrary to the results of many other investigators, that increased soil humidity did not decrease the relative quantity of grain in wheat plants.

Preul (1908) brought out the facts that abundant soil moisture succeeding a dry period produces a high grain yield in wheat, and that dry soil at the time of heading is especially harmful. A lack of water during later stages of growth lowered the weight of one thousand kernels, especially on rich soil.

Gain (1895b) showed that, while dry soils decrease the number of seeds produced, the seeds that are grown are larger and heavier than those grown on wet soils.

Le Clerc (1907) observed that the weight of one thousand kernels is usually greater in wheat from irrigated and humid regions, while arid regions produce a higher percentage of flinty kernels.

Von Seelhorst and Bünger (1907) found that the number of kernels of wheat per head rise with the following conditions: (1) an increase in soil moisture; (2) high nitrogen fertilizer; (3) usually with a thin stand; and (4) large heads. They found also that the weight of one thousand

kernels is influenced as follows: (1) nitrogen fertilizer lessens the weight of kernels on low soil moisture, but raises it with high moisture; (2) high moisture lowers the weight on nitrogen-poor soil, but increases it on nitrogen-rich soil; (3) a thick stand usually lessens the weight of kernels.

Lyon (1905) showed that plants bearing the largest number of kernels have kernels of more than medium, but not the greatest, weight; also that the weight of the average kernel does not increase with the size of the head, nor does it decrease except on the very largest heads.

Widtsoe and his associates at the Utah Agricultural Experiment Station[2] have contributed greatly to our knowledge of the effect of irrigation water on soils and on crops. The advantage of these experiments is that they were conducted in the field under regular cropping conditions. Medium applications of water were found to be the best in economizing moisture.

Transpiration

Sachs, Burgerstein, and others have long since shown that certain substances in the soil and in culture solutions may greatly retard or accelerate the rate of transpiration in plants.

Reed (1910) did considerable work on the specific effect of certain acids, bases, and salts on transpiration in wheat seedlings grown for two or three weeks.

Gain (1895a) brought out many points in regard to transpiration. He showed that it is increased with high soil moisture until the " maximum of turgescence " is passed, after which it decreases.

Abbe (1905) gave the factors influencing transpiration as follows: (1) quantity of water available to the plants; (2) temperature and dryness of the air; (3) velocity of the wind; (4) intensity of the sunlight; (5) stage of development of the plant; (6) quantity of foliage; and (7) nature of the leaf. He records that it was found by S. H. Woodward, as early as 1691, that the amount of water necessary to increase one gram in the weight of plants varies with the amount of nourishment in the water — the water of the Thames River, with its considerable supply of plant-food, being used much more economically than pure spring water. Abbe showed that the amount of water used in producing a given amount of dry matter varies with the season.

Lawes (1850) concluded, after using a number of fertilizers with wheat, barley, beans, peas, and clover, that there is a greater economy in the water transpired by wheat, peas, and clover when mineral fertilizers are present, but that with beans, under certain conditions, the fertilizers produce the opposite effect.

[2] See bibliography, under Widtsoe and others, pages 867 and 868.

Heinrich (1904) showed that the humidity of the atmosphere influences the relationship between the water transpired by oats and the dry matter produced. In an atmosphere kept constantly humid, only 102 grams of water were transpired for each gram of dry matter, while in the dry atmosphere 618 grams were required. Heinrich showed also that plants growing in a concentrated nutrient solution transpire water more economically than when growing in a dilute solution.

Maercker (1896) concluded that dry matter is produced with less water when potash salts are used as fertilizer.

Schroeder (1896) found that the transpiration of barley is in proportion to soil humidity and the concentration of the nutritive material present. The quantity of water evaporated per unit of dry matter increases with the concentration of the medium until the latter reaches a certain concentration, beyond which it falls.

King, whose work is described in the annual reports of the Wisconsin Agricultural Experiment Station from 1891 to 1893, has perhaps studied, more than any one else in this country, the relation between transpiration and dry weight of crops produced. He worked out the average quantity of water used by a number of crops under Wisconsin conditions (1907: 139). He showed also that rapidly growing, vigorous plants produce more dry matter with the same quantity of water than do weaker plants, and that water is used more economically on summer-fallowed than on continuously cropped land (1893a and 1894a).

Pagnoul (1898) found that in poor soil about twice as much water is required in order to produce a unit of dry substance in fescue grass as in rich soil.

Von Seelhorst (1899) found, with oats, that the water required in order to produce a unit of dry weight decreases as the luxuriance of growth increases; also that the balance between the fertilizer constituents, as well as the nature of the soil, influences the relation between water used and dry substance produced. He later (1906) found that water is used more economically on a loam than on a sandy soil.

Warington (1900), comparing the results of Lawes and Gilbert, Hellriegel, King, and Wollny, concluded that the relation between water used and crop produced is influenced, first, by the quantity of water supplied, and second, by the richness or poverty in plant-food.

Yanovchik (1900) observed that wheat transpires water more economically with a medium soil humidity than with soil very wet or very dry.

Fortier's (1903) results from applying irrigation water to oats in tanks show that more water is used in producing a pound of dry weight of crop with both the very large and the very small irrigations than with the medium irrigations.

Morgan (1912), working with plants in wire baskets, also found a medium degree of soil moisture most economical in producing dry matter.

Widtsoe (1902) showed that crops require more water in order to produce a pound of dry matter in arid than in humid regions. He later (1909) worked out the effect of a number of factors in affecting the relation between transpiration and dry substance produced. The fallowing and cultivation of the soil, the soil fertility and humidity, the season, the crop, and the method of applying water, were all shown to be important in affecting this relation. Fertile soils and summer-fallowed soils were especially economical in their use of water.

Livingston (1905) concluded that transpiration and growth are proportional under various conditions; but his results, as well as those of other experimenters, do not justify this conclusion.

Gardner (1908) found that fertilizers which are most efficient in increasing the green weight of seedlings also cause water to be transpired most economically.

Preul (1908) found, with wheat seedlings in zinc tanks, that less water is required for a unit of dry substance in fertile soil than in poor soil.

Kiesselbach (1910) concluded that soil humidity, and concentration of nutrient solution added to corn, have no great effect on the relation between dry matter and water transpired. His tables, however, do indicate differences for both these factors.

Heinrich (1904) showed that the absolute amount of water transpired increases from week to week until about the time of blooming, and then decreases.

Livingston (1906), studying soil moisture and evaporation in relation to desert plants, concluded that the temperature of the air is the most important factor in controlling transpiration.

Leather (1910–1911), working in India, investigated a number of the factors influencing the water transpired by certain of the crops. Soil moisture and fertilizers were given particular attention.

Bouyoucos (1912) found that there is a close relation between the concentration of the nutrient solution and the transpiration ratio. Increasing the density of the solution caused water to be used more economically. The various ions in the solution were found to exert an influence on the economy of transpiration.

Lyon and Bizzell (1913 a) have shown that a greater quantity of dry matter per unit of transpiration is produced in fertilized than in unfertilized soil, and they suggest the use of this transpiration ratio as a means of determining the relative density of the soil solutions.

Montgomery and Kiesselbach (1912) found that manure decreases the water requirements of corn; but they doubt whether, under field con-

ditions, adding manure to soils of good fertility would decrease the water requirements.

Briggs and Shantz (1913, a and b) have prepared a good summary of literature on the water requirements of plants, and they report a number of experiments made under their direction during 1910 and 1911. They show the effect of crop and variety, as well as of climate, on the quantity of water required in order to produce a unit of dry matter. At Akron, Colorado, alfalfa used the greatest quantity of water, while millet used the least. Wheat required about twice as much as millet and about one half as much as alfalfa.

Khankhoje (1914), working at the Washington Agricultural Experiment Station, found the following factors to influence the water requirements of crops: (1) kind of crop; (2) strength of soil solution; (3) age of plants; (4) amount of moisture in the soil.

Relation of moisture and fertilizers to the composition of plants

Nitrogen.— Mayer (1898), working for a number of years with rye, wheat, barley, and oats, found that, as a rule, the less the moisture, the lower is the percentage of fiber and the greater is the percentage of protein and pure albuminoids. The water requirements of these plants were placed in the following order, from greatest to least: oats, wheat, rye, barley.

Wilms and von Seelhorst (1898) pointed out that increasing the soil moisture reduces the nitrogen content of both grain and straw of oats, but that variations in nitrogen content due to water supply are more marked in straw than in grain. The nitrogen content of the crop is affected also by fertilizers. Similar results were obtained by Prianishnikov.

Widtsoe (1902), working under irrigation conditions with corn, wheat, potatoes, and sugar beets, found that with the same climatic conditions a high amount of irrigation water diminishes the percentage of protein but increases the percentage of nitrogen-free extract and fat. In wheat the protein was eleven per cent higher when grown with low irrigation than when grown with high irrigation.

Traphagen (1903) showed that when low-protein wheat from an irrigated field is planted under dry conditions the percentage of protein is greatly increased.

Whitson and Stoddart (1904) observed a higher percentage of protein in crops grown on soil with a good supply of nitrates than in crops grown on soil with a low supply of nitrates.

Von Seelhorst and Fresenius (1905) showed that with oats a high soil moisture causes a lower rate of decrease in the proteid nitrogen than

in total nitrogen, also a less decrease in the digestible proteid nitrogen than in the total proteid nitrogen.

Lyon (1905) pointed out that the increase in nitrogen due to a deficiency of moisture is often caused by the shortening of the growing period, and that the weight of proteid nitrogen in the average kernel is less in the early-maturing plants. He showed also (1910) that hardness of kernel and high percentage of nitrogen are always associated.

Le Clerc (1907), comparing a large number of results with wheat grown under humid and under arid conditions, found that high nitrogen is associated with arid conditions.

Preul (1908) showed that the nitrogen content of grain and straw grown on rich soil is higher than in that grown on poor soil; also that constant low moisture, on both rich and poor soil, increases the percentage of nitrogen, but a lack of moisture at late stages of growth lowers the nitrogen content of grain. In the case of straw, the nitrogen content is lowered on the rich soil but increased on the poor soil.

Shutt (1909) pointed out that in Manitoba newly broken land, as well as moist irrigated soil, produced starchy grain lower in nitrogen than grain grown on old soil or soil with a low moisture content.

Frei (1910) found the nitrogen content of oats to be influenced by moisture, distance of planting, quality of soil, and a number of other factors.

Hunt (1904) states that "a cool, prolonged, but not too wet spring, followed by moderately dry sunny weather during ripening, is most favorable to the largest yield of the best quality" of wheat. He also believes any shortening of the period of growth to be the chief factor in raising the percentage of nitrogen in wheat.

Schindler (1893), as early as 1893, stated that the protein content of the wheat kernel depends in the first place on the length of the growing period, and secondly on the richness of the soil.

Thatcher (1912 and 1913) has done a large amount of work on the factors affecting the composition of wheat. He held that the relative protein content of grain is determined chiefly, if not wholly, by the rapidity of ripening of the kernel after it is once formed. He found also that the moisture supply is a very important factor in determining the composition of wheat grown in any given locality or season.

Ash constituents of plants.— Wilms and von Seelhorst (1898) discovered that the ash content of grain varies with the quantity of water in the soil, increasing rapidly up to the point of medium water supply, but more slowly beyond that point. The fertilizer producing the lowest yield of grain gave grain with the highest percentage of ash. The effect of moisture and fertilizers on the potassium and phosphorus content

of the ash under various conditions was also worked out in some detail.

Von Seelhorst, Georgs, and Fahrenholtz (1900) found that the percentage of ash in rye grass and in clover usually increases as the soil moisture increases, up to the limits used by them.

Gamble (1906) found plants grown in surface soil in pots to have a somewhat higher ash content than plants grown in the field. This was attributed in part to the moisture supply.

Hall (1905) has given some very interesting data regarding the ash of grain and straw as affected by manures and by the season at Rothamsted.

Le Clerc (1907) did not find any great difference in the percentage of ash and of phosphoric acid in grain grown under humid and under arid conditions.

Fest (1908) showed the effect of various fertilizers added to the soil on the composition of the ash of dwarf beans, and brought out many interesting relations. For example, a lack of nitrogen caused a decrease in nitrogen and potassium, but an increase in calcium.

Von Daszewski and Tollens (1900) found that soil moisture has a great influence on the ash of the potato. With high soil moisture the potato took up a larger amount absolutely, and a smaller amount relatively, of potassium and phosphoric acid, than with lower soil moisture. Relatively more calcium and chlorine, however, were taken up with the higher moisture.

Composition of plants at different stages of growth.— It was repeatedly observed, many years ago, that plants take up their mineral matter and nitrogen much faster while young than when they become older.

Hébert (1892) found that the percentage of nitrogen and that of ash are very high in oats and wheat at first, and gradually decrease to maturity.

Davidson (1895), working with tobacco, discovered that the percentage of total ash and that of most of the ash constituents are much greater during early periods than later. The percentage of calcium, however, is highest at the time of cutting.

Schulze (1904) concluded, from his experiments with rye and wheat, that practically all the assimilation of nitrogen, phosphoric acid, potash, and sulfur is complete at the time of heading. Calcium and magnesium are used to a somewhat greater degree during later stages.

Wilfarth, Römer, and Wimmer (1906), after years of work with a number of crops, advanced the theory that there is an actual return of mineral substances and nitrogen from the plant to the soil during the late stages of growth; this return being more marked with certain constituents and with certain crops than with others. Similar results have been obtained by Wagner (1908), Fest (1908), Seidler and Stutzer (1908), Déléano (1907), and a number of others. Le Clerc and Breazeale (1909), however, believe

this return to be due mainly to the washing-off of the ash constituents by rain water, rather than that it is a real return through the roots.

Conditions of the experiments, and methods used

The experiments reported in the following pages were conducted in the greenhouse of the Department of Soil Technology at Cornell University during the winters of 1908–1909 and 1909–1910, and the analyses were made later in the laboratory of the same department.

The pots

Wheat plants were raised in three-gallon glazed earthenware pots containing a special device for measuring transpiration. This transpiration-measuring device, or potometer, which is essentially the one devised by Professor Montgomery at the Nebraska Agricultural Experiment Station, was arranged as follows: An ordinary earthen flowerpot three inches in diameter, containing a hole in the bottom, was inverted in the culture pot mentioned above. A thistle tube fifteen inches long had an inch or so of its lower end turned up to form a U. This was placed under the edge of the small inverted pot so that the lower end of the thistle tube was inside this pot, while the bowl end projected out above the large pot and served as a receiver for the water, which was conducted into the inverted pot below. From here the water could run out into the surrounding soil. There was also a glass tube to conduct the air out of the inverted pot when water was added. A small quantity of fine gravel was placed in the bottom of the main pot around the inverted pot, to improve aëration and facilitate the movement of water into the soil.

Soil having been put into the culture pot, the wheat was planted in two rows, then one half kilogram of crushed quartz was placed over the surface to serve as a mulch. When the plants were three or four inches high the pots were sealed with paraffined paper, in which were holes to allow the plants and the glass tubes to pass through. Thus there could be no escape of water except that transpired through the plants. The pots were weighed three times a week, and the loss that had occurred was made up with distilled water, which was added through the thistle tube as a subirrigation.

The soil

The soil used was taken from Caldwell Field, Plat 729, and had received no fertilizer for many years. It is described by the United States Bureau of Soils as the silty phase of Dunkirk clay loam.

A chemical analysis of the soil made from the extract of HCl sp. gr. 1.115 gave the following:

TABLE 1. CHEMICAL ANALYSIS OF SOIL

Constituents	Percentage
CaO	0.54
MgO	0.56
K_2O	0.183
Fe_2O_3	2.66
Al_2O_3	3.64
P_2O_5	0.15
Nitrogen	0.12
Moisture	1.54

Nine kilograms of moist soil were placed in each pot. This was equivalent to 7.65 kilograms of dry soil in 1908–1909 and to 7.70 kilograms in 1909–1910. Thus practically the same quantity of soil was used for each pot during the two years.

Fertilizers

During both years some of the pots were unfertilized and some were fertilized, two combinations being used. One set received the following:

Nitrate of soda, 0.771 gram per pot, or 300 pounds per acre
Muriate of potash, 0.257 gram per pot, or 100 pounds per acre
Acid phosphate, 0.771 gram per pot, or 300 pounds per acre

This combination was called "complete fertilizer," and will be so distinguished throughout the report of the experiments.

The other combination used will be distinguished as "high nitrogen fertilizer," and was as follows:

Nitrate of soda, 2.57 grams per pot, or 1000 pounds per acre
Muriate of potash, 0.257 gram per pot, or 100 pounds per acre
Acid phosphate, 0.771 gram per pot, or 300 pounds per acre

These fertilizers were added to the surface of the soil as dry salts, and were stirred into the upper two or three inches before the seeds were planted.

Stages in the plant growth

The life of the plant was divided into three stages, as follows: first, from planting until the plants had five well-developed leaves; second, from the five-leaf stage until the swelling of the culms showed the development of the head (this will be designated by its popular name, "boot stage"); third, from the boot stage to maturity. Some pots were kept

at the same humidity throughout the three periods, while others were changed during each period. All received the same quantity of water at first, in order to insure even germination; but when the plants were up, all pots received their proper quantity of moisture. Thirty seeds were planted in each pot, but when the plants were a few inches high all were removed except twelve plants of a uniform size. Duplicates were kept of all the cropped pots.

Arrangement and treatment of pots during 1908–1909

The following is the treatment received by the respective pots during 1908–1909. All moisture is stated on the basis of percentage of dry soil. The water-holding capacity of the soil was about 45 per cent of its dry weight when the pots were filled, consequently 15 per cent and 30 per cent of water as given would be 33 per cent and 67 per cent, respectively, of its water-holding capacity.

The uncropped pots, which were allowed to stand by the side of the cropped ones in order to determine the changes going on in the soil, were arranged as follows:

TABLE 2. TREATMENT OF UNCROPPED POTS, 1908–1909

Fertilizer	Percentage of soil moisture
Complete	30 at first, gradually decreased to 15
Complete	15 throughout
Complete	30 throughout
None	15 throughout
None	30 throughout

In the cropped soil the variety of wheat used was Pringle's Champion, from Montana. The following was the arrangement of pots and the treatments received, there being duplicate pots for all treatments:

TABLE 3. TREATMENT OF CROPPED POTS, 1908–1909

Percentage of soil moisture		
First stage	Second stage	Third stage
30	30	30
30	30	15
30	15	15
15	15	15
15	15	30
15	30	15

This series was conducted for each of the three fertilizer treatments, making six pots for each moisture treatment.

On November 30, 1908, a second series, arranged as follows, was planted, to be harvested and analyzed at various stages, there being pots receiving 15 per cent and 30 per cent of moisture for each fertilizer, harvested both at boot stage and at time of bloom.

TABLE 4. TREATMENT OF SECOND SERIES OF POTS, 1908–1909

Percentage of soil moisture	Period of harvest
15	Bloom
15	Boot
30	Bloom
30	Boot

Arrangement and treatment of pots during 1909–1910

During the winter of 1909–1910 the treatments were as follows. The variety of wheat used was Galgalos, and it was planted on October 16, 1909.

TABLE 5. TREATMENT OF UNCROPPED POTS, 1909–1910

Fertilizer	Percentage of soil moisture
None	30 throughout
None	15 throughout
Complete	30 throughout
Complete	15 throughout
High nitrogen	30 throughout
High nitrogen	15 throughout
None	11 throughout
None	13 throughout
None	20 throughout
None	25 throughout
None	37½ throughout
None	45 throughout

TABLE 6. TREATMENT OF CROPPED POTS, 1909–1910

Fertilizer	Percentage of soil moisture
None	11 throughout
None	13 throughout
None	20 throughout
None	25 throughout
None	37½ throughout
None	45 throughout

As in 1908–1909, the following moisture treatments in duplicate were conducted for each of the fertilizer conditions:

TABLE 7. TREATMENT OF CROPPED POTS IN DUPLICATE, 1909–1910

Percentage of soil moisture		
First stage	Second stage	Third stage
30	30	30
30	30	15
30	15	15
15	15	15
15	15	30
15	30	15

The methods of analysis and of making the various measurements will be given in connection with the results.

EFFECTS ON THE SOIL

A study was made of the soils in the cropped and the uncropped pots. These soils, having stood for a considerable time under the conditions previously described, had the following properties examined, some being studied during both years of the experiment while others were studied for but one season: (1) volume of the soil; (2) flocculation of the soil particles; (3) nitrates; (4) nitrites; (5) ammonia; (6) total water-soluble salts; (7) number of bacteria; (8) easily soluble phosphoric acid.

The method of taking soil samples was as follows: In 1908–1909 a hollow cylinder was pressed into the soil to the bottom of the pot in six or seven places, and the soil thus removed was thoroughly mixed. This method was employed in order that the root system might not be greatly disturbed. In 1909–1910, after the plants were harvested all the soil in a pot was removed and thoroughly mixed. Samples of this fresh soil were then taken for the determination of total water-soluble salts, nitrates, nitrites, and ammonia. Some of the soil was spread out to become air-dry, and was used later in determining the flocculation and the easily soluble phosphoric acid.

Volume of the soil

Each pot contained the same dry weight of soil, so that any difference in volume was due to the extra packing produced by the treatments given. The volume was determined at the close of the experiment, by getting the average depth of the soil in the pot and the diameter of the pot, and calculating from these the total volume, then deducting the volume occupied by the small inverted pot previously described.

The latter volume was obtained by water displacement. The volume is expressed in cubic centimeters.

TABLE 8. VOLUME OF CROPPED AND OF UNCROPPED SOIL WITH DIFFERENT QUANTITIES OF MOISTURE, 1909–1910

Soil moisture (percentage)	Cropped soil		Uncropped soil		Average volume of soil for cropped and uncropped
	Number of pots	Volume of soil per pot (cubic centimeters)	Number of pots	Volume of soil per pot (cubic centimeters)	
11	2	7,500	1	8,060	7,687
13	2	7,680	1	7,920	7,760
15	6	7,535	6	7,723	7,629
20	2	7,300	1	7,850	7,483
25	2	7,470	1	7,480	7,473
30	6	6,987	6	7,463	7,225
37½	2	6,365	1	6,610	6,447
45	2	6,220	1	6,130	6,190
Total	24	.....	18	.....	.....
Average	.....	7,175	.....	7,509	.....

From the table it is clear that the cropped soil became more compact than did the uncropped soil, and that the volume decreased as the wetness of the soil increased. It is not easy to see why the cropped soil should occupy less space than the uncropped. The explanation may be found in the fact that the cropped soil had water added to it much oftener than did the uncropped, and each addition of water tended to pack the soil somewhat. It is rather surprising that the difference in volume between the wet and the dry soil should be so great, especially since they had about eight months in which to settle.

TABLE 9. EFFECT OF FERTILIZERS ON VOLUME OF CROPPED SOIL. AVERAGE FOR ALL MOISTURE TREATMENTS. 1909–1910

Fertilizer	Number of pots	Average volume of soil in each pot (cubic centimeters)
None	12	7,388
Complete	12	7,272
High nitrogen	12	7,110

The fertilized soil, and especially that with high nitrogen, was more compact than the unfertilized. A possible explanation of this is that the fertilized soil, by producing larger crops, required more water to be added each time, and this greater quantity of water packed the soil more. Another possible cause is the deflocculating action that sodium nitrate in large quantity has been shown to exert on heavy soil. The fact that the pots receiving the heavier application of nitrate contained the most compact soil would indicate that the quantity of the nitrate was a factor.

TABLE 10. EFFECT OF CHANGING THE MOISTURE CONTENT AT DIFFERENT STAGES OF PLANT GROWTH ON THE VOLUME OF CROPPED SOIL. AVERAGE FOR ALL FERTILIZER TREATMENTS. 1909–1910

Percentage of soil moisture			Number of pots	Average volume of soil per pot (cubic centimeters)
First stage	Second stage	Third stage		
30	30	30	6	6,987
30	30	15	6	7,122
30	15	15	6	7,273
15	15	15	6	7,535
15	15	30	6	7,432
15	30	15	6	7,192

The soil continually wet was the most compact, and that continually dry was the least compact. Where it was wet for two periods it was more compact than where it was wet for but one period; and being wet during a period when the plants were young had a greater compacting effect than being wet for the same length of time when the plants were old.

Flocculation of the soil particles

In order to determine the amount of flocculation of their particles, some of the soils used during 1909–1910 were tested by the suspension method, as follows: Ten grams of air-dry soil was weighed out into an evaporating dish. Twenty-five cubic centimeters of distilled water was poured over this, to wet it thoroughly, and it was allowed to stand for a few minutes. The wet soil was washed into a glass cylinder and made up to 600 cubic centimeters with distilled water. The mouth of the cylinder was covered with the hand, and the cylinder was shaken vigorously a number of times and was then allowed to stand for one hour. Fifty cubic centimeters of the water with its suspended soil was pipetted off, the tip of the pipette being placed 25 centi-

meters from the bottom of the cylinder. This soil was evaporated to dryness in a weighed platinum dish, was weighed, and the amount of suspended soil was determined by subtracting. The soluble matter would also be present, but the amount would be so small compared to the suspended matter that it would be negligible. Of course, the greater the flocculation of particles, the less is the suspended matter.

The results showed that flocculation decreases as the moisture increases, and it was especially small in the very wet soil. There was but very little difference in the soils with small or medium quantities of moisture; indeed, the 20 per cent moisture seemed, on the whole, about the most favorable to flocculation. There was much better flocculation in the cropped than in the uncropped soil. The crop increased flocculation to the greatest extent on the very wet soil. This shows that when a soil is very wet its physical condition is likely to be much better if a crop is grown on it than if it is allowed to lie bare.

Nitrates

Nitrates, nitrites, and ammonia were determined by the method described by Schreiner and Failyer (1906). One hundred grams of soil was stirred with 500 cubic centimeters of distilled water for three minutes and allowed to stand for twenty minutes. It was then filtered through Chamberlain-Pasteur filters under pressure, and 50 cubic centimeters of the filtrate was taken for the determination of the nitrates. Portions of this same filtrate were also used for the determination of nitrites, ammonia, and total water-soluble salts. The nitrates are expressed in parts per million of NO_3 on the basis of dry soil.

TABLE 11. EFFECT OF FERTILIZERS AND OF HIGH AND LOW SOIL MOISTURE ON NITRATES IN CROPPED AND IN UNCROPPED SOIL. RESULTS FOR TWO YEARS

Fertilizer	Nitrates (in parts per million of dry soil)							
	1908–1909				1909–1910			
	Cropped		Uncropped		Cropped		Uncropped	
	30 per cent moisture	15 per cent moisture	30 per cent moisture	15 per cent moisture	30 per cent moisture	15 per cent moisture	30 per cent moisture	15 per cent moisture
None	2.9	32.1	296	15.2	17	10	233	177
Complete	2.8	35.6	396	35.1	33	9	286	269
High nitrogen	3.4	131.4	.....	.....	27	32	399	428

The very striking thing shown in this table is the way in which the nitrates are kept down by the crop. With high nitrogen fertilizer and 15 per cent moisture during 1908-1909, there was a very poor crop and the nitrates in the soil ran high. On the uncropped soil the nitrates were usually higher with 30 per cent moisture than with 15 per cent. This was probably due to the fact that the larger crop on the wetter soil took up the excess of nitrates. The fertilized soils had more nitrates than did the unfertilized ones, due, no doubt, to nitrates added in the fertilizer.

TABLE 12. EFFECT OF DIFFERENT SOIL MOISTURE CONTENTS ON NITRATES IN CROPPED AND IN UNCROPPED SOIL. NO FERTILIZER. 1909–1910

Soil moisture (percentage)	Nitrates (in parts per million)	
	Cropped	Uncropped
11	38	Lost
13	21	188
15	10	177
20	19	156
25	23	195
30	17	233
$37\frac{1}{2}$	29	193
45	Trace	3
Average	20	164

Here again the effect of the crop in reducing the nitrates is very marked. All quantities of moisture below 25 per cent seemed to affect nitrification in about the same manner. Thirty per cent was the most favorable for nitrification, while $37\frac{1}{2}$ per cent was decidedly inferior; and with 45 per cent there was actual denitrification, since the soil contained 36 parts per million nitrates when put in the pots. The soil with 45 per cent water was completely saturated, and when removed from the pots it had a bluish, mottled appearance and a strong odor of putrefaction, showing a lack of aëration. Notwithstanding the fact that the larger crops on the more moist soils removed more nitrates than were removed by crops on the drier soils, still nitrification seemed to keep pace with the more rapid removal.

Further data regarding nitrates in cropped soil will be given in connection with the total soluble salts.

Nitrites

None of the soil solutions contained more than merely a trace of nitrites, and the quantity present in soils under the conditions of the experiment

is certainly too small to be of any great importance; but the delicacy of the method of determination allowed a few interesting points to be brought out.

It was shown that the cropped soils were in most cases almost free from nitrites, while most of the uncropped soils had very appreciable quantities. The wettest soil, which contained very low nitrates, had the most nitrites. Other data for nitrites are found in connection with the total soluble salts.

Ammonia

The quantity of ammonia in the water extract was small and did not seem to be so much affected by the treatment as were the other constituents. A small quantity of ammonia was usually present, but it was never very much.

The striking feature about the results was the fact that ammonia was always higher in the cropped than in the uncropped soil. This is just opposite to the conditions with nitrates, nitrites, total water-soluble salts, and easily soluble phosphoric acid. The quantity of ammonia in the soil did not seem to be greatly affected by the soil moisture. It was always greater, however, with $37\frac{1}{2}$ per cent than with any other humidity.

Total water-soluble salts

The total soluble salts in the water extract mentioned above were determined by means of the electrical resistance method used by King and by the United States Bureau of Soils, and described in Bulletin No 61 of that bureau. This method, of course, gives only the electrolytes present, but these electrolytes comprise most of the material dissolved from soils by water.

TABLE 13. EFFECT OF FERTILIZERS AND OF HIGH AND LOW MOISTURE ON THE TOTAL SOLUBLE SALTS IN CROPPED AND UNCROPPED SOILS. RESULTS FOR TWO YEARS

Fertilizer	Total soluble salts (in parts per million of dry soil)							
	1908–1909				1909–1910			
	Cropped		Uncropped		Cropped		Uncropped	
	30 per cent moisture	15 per cent moisture	30 per cent moisture	15 per cent moisture	30 per cent moisture	15 per cent moisture	30 per cent moisture	15 per cent moisture
None	101	128	447	254	97	86	360	296
Complete	94	234	652	580	148	110	431	468
High nitrogen	193	489	.....	.....	122	150	662	635

The effect of the crop was to reduce the total soluble salts, but in a less degree than it reduced the nitrates. The fertilized soils gave more soluble salts than did the unfertilized, and where there was a crop the high nitrogen fertilizer was more effective in this regard than the complete fertilizer. The relation between the soluble salts in the moist and in the dry soils usually seemed to be different where there was a high nitrogen fertilizer present from what it was under the other conditions, the wet soil having more salts in one case and the dry having more in the other.

TABLE 14. TOTAL SOLUBLE SALTS, AND RATIO OF SOLUBLE SALTS TO NITRATES, IN CROPPED AND IN UNCROPPED SOIL WITH DIFFERENT MOISTURE CONTENTS. NO FERTILIZER. 1909–1910

Soil moisture (percentage)	Total soluble salts (in parts per million of dry soil)		Ratio of total soluble salts to nitrates	
	Cropped soil	Uncropped soil	Cropped soil	Uncropped soil
11	109	309	2.9 : 1	.....
13	83	258	4.0 : 1	1.4 : 1
15	86	296	8.6 : 1	1.7 : 1
20	85	267	4.5 : 1	1.7 : 1
25	88	270	3.8 : 1	1.4 : 1
30	97	360	5.7 : 1	1.5 : 1
37½	95	253	3.3 : 1	1.3 : 1
45	95	100	95.0 : 1	33.3 : 1
Average	92	264	4.6 : 1	1.6 : 1

The relations shown between the cropped and the uncropped soil are similar in Table 14 to what they were in the previous table. The soil with 30 per cent moisture contained the most salts, while that with 45 per cent had the least, where there was no crop. The soil with 11 per cent moisture — both cropped and uncropped — had more salts than did the soil with medium moisture.

The ratio between soluble salts and nitrates shows some very interesting relations. The nitrates were always proportionately lower in the cropped soils, which fact shows that plants take up the nitrates proportionately faster than the other soluble salts. The low relative amount of nitrates in the very wet soil shows that the excess of water interfered with nitrification more than with the making soluble of other salts.

The nitrates were influenced much more by changing the moisture than were the other constituents. Where the moisture had been high

and was lowered, the nitrates were lower than where it was raised or where it was kept constantly high or low. This lower amount in one case may, however, be due entirely to the crop on the soil.

TABLE 15. EFFECT OF HIGH AND OF LOW SOIL MOISTURE DURING DIFFERENT PERIODS ON NITRATES, AMMONIA, AND TOTAL SOLUBLE SALTS IN CROPPED SOIL. AVERAGE FOR ALL FERTILIZER TREATMENTS. 1909–1910

Percentage of soil moisture			Number of pots	Parts per million			Ratio of soluble salts to nitrates
First stage	Second stage	Third stage		Nitrates	Ammonia	Total soluble salts	
30	30	30	6	27	1.37	122	4.5:1
30	30	15	6	9	1.27	102	11.3:1
30	15	15	6	24	1.28	116	4.8:1
15	15	15	6	32	1.24	115	3.6:1
15	15	30	6	27	1.57	115	4.3:1
15	30	15	6	13	1.15	108	8.3:1

TABLE 16. EFFECT OF FERTILIZERS ON NITRATES, AMMONIA, NITRITES, AND TOTAL SOLUBLE SALTS IN CROPPED AND IN UNCROPPED SOILS. 1909–1910

Fertilizer	Number of pots	Parts per million				Ratio of soluble salts to nitrates
		Nitrates	Ammonia	Nitrites	Total soluble salts	
Cropped soil						
None.....	12	12	1.26	.....	88	7.3:1
Complete....	12	16	1.28	.....	121	7.6:1
High nitrogen	12	33	1.40	.....	130	3.9:1
Uncropped soil						
None.....	4	205	.81	.038	328	1.6:1
Complete....	4	278	.82	.034	450	1.6:1
High nitrogen	4	414	1.68	.157	649	1.6:1

The nitrates, ammonia, nitrites, and total soluble salts were all highest in the soil receiving the high nitrogen fertilizer. This condition held for both the cropped and the uncropped soil. As stated previously, the ammonia is the only constituent determined that was higher in the cropped than in the uncropped soil, but in this table the condition does not hold for the soil with high nitrogen. Where there was a crop the ratio of total salts to nitrates was much less with the high nitrogen fertilizer. This, of course, is what would be expected. On the soil without a crop

the ratio of total salts to nitrates did not seem to be affected to any extent by the fertilizers. There appeared to be a sort of equilibrium established between the two, with about 1.6 total salts to 1 unit of nitrates. When there were plants on the soil, however, proportionately more of the nitrates were taken up, with the effect that the ratio was widened.

Number of bacteria[3]

Samples of soil were taken from eight of the uncropped pots which had stood in the greenhouse with a constant moisture content for about eight months, and a count of the bacteria was made. The following methods were used in obtaining the counts:

The soil was sampled by pushing a hollow cylinder down to the bottom of the pot, and then removing the cylinder with the soil. This was done in five or six places in each pot, and the soil was thoroughly mixed in the laboratory by sifting. Sterile water and sterile flasks were prepared, and 0.5 gram of the mixed soil was added to 100 cubic centimeters of water and vigorously shaken for two minutes; then the contents of the flask were whirled in motion, and 1 cubic centimeter of the suspension was removed with a sterile pipette while the liquid was in rapid action. This 1 cubic centimeter was again diluted to 100 cubic centimeters with sterile water, making a strength such that 1 cubic centimeter represented $\frac{1}{20,000}$ gram of soil. During all this process care was taken to prevent air infection. One cubic centimeter of the last-mentioned dilution was added to each petri dish, and 10 cubic centimeters of the melted gelatin medium was added and was mixed with the suspension by tilting the dish backward and forward for some time. The following medium was used: dextrose 1 gram, gelatin 120 grams, soil extract 200 cubic centimeters, and water to make 1000 cubic centimeters. Reaction, 5 per cent acid. The soil extract for the medium was made as follows: 5 kilograms of soil, previously sterilized for one hour at two atmospheres pressure, was diluted with 10 liters of water and allowed to stand over night. This was boiled for one hour, the amount of water replaced, then filtered, and the filtrate was used as the soil extract in the medium.

Six petri dishes were used for each soil. The plates were allowed to incubate for seven days at a temperature of 19° to 20° C., and the number of colonies were then counted and the counts reduced to a basis of the dry soil. The number of bacteria varied from 1,750,000 to 5,000,000 for each gram of soil.

It was rather difficult to draw any conclusions regarding the effect of the treatments on the number of bacteria. It seemed, however, that the number was slightly higher with 15 per cent than with 30 per cent moisture;

[3] The author is indebted to his associate, Dr. H. J. Conn, for the bacteria counts.

also, the fertilizer seemed to have a slightly depressing effect. The differences, however, were not great enough to justify any conclusions.

Easily soluble phosphoric acid

It was thought desirable to determine the easily soluble phosphoric acid in the cropped and the uncropped soils that had stood for nearly a year with different moisture contents and different fertilizers.

The soil was removed from the pots and thoroughly mixed, and large samples were taken and air-dried. This air-dry soil remained in glass jars for a number of months before the determinations were made.

The extract of the soil was made according to the official methods of the Association of Official Agricultural Chemists for the "more active forms of phosphoric acid." That is, 2000 grams of the air-dry soil was digested for five hours at 40° C. with N/5 HCl, corrected for the amount neutralized by the soil, was filtered, and 1000 cubic centimeters was evaporated to dryness, after the addition of a few drops of HNO_3. This mass was moistened with HCl, taken up with water, filtered, and the P_2O_5 in the filtrate was determined volumetrically according to the method described by Williams (1895), the precipitation with molybdate solution being made twice. All determinations were made in duplicate.

TABLE 17. EASILY SOLUBLE PHOSPHORIC ACID IN CROPPED AND IN UNCROPPED SOILS WITH DIFFERENT MOISTURE CONTENTS. 1909–1910

Soil moisture (percentage)	Cropped soil		Uncropped soil	
	Number of pots	P_2O_5 (in parts per million of dry soil)	Number of pots	P_2O_5 (in parts per million of dry soil)
11	2	64	1	97
13	2	100	1	117
20	2	105	1	113
25	2	81	1	114
37½	2	78	1	96
45	2	110	1	116
Average	.....	90	.....	109

From the table it is seen that in every case the easily soluble phosphoric acid was higher on the uncropped than on the cropped soil with the same percentage of moisture, the average for the cropped soil being 90 parts per million and that for the uncropped 109 parts per million.

The quantity of phosphoric acid dissolved was quite different for various moisture treatments, but it did not vary regularly with the moisture. The lowest moisture gave the lowest phosphoric acid; then as the moisture rose there was an increase; with $37\frac{1}{2}$ per cent moisture the phosphoric acid was again low, but it rose again with 45 per cent moisture. The results appear rather strange, but the fact that the cropped and the uncropped soils agree so well makes them significant.

TABLE 18. EASILY SOLUBLE PHOSPHORIC ACID IN UNCROPPED SOIL WITH HIGH AND LOW MOISTURE AND WITH DIFFERENT FERTILIZERS. 1909–1910

Soil moisture (percentage)	P_2O_5 (in parts per million of dry soil)		
	No fertilizer	Complete fertilizer	High nitrogen fertilizer
30	81	136	116
15	82	123	117
Average	82	130	117

There seemed to be but little difference in the phosphoric acid whether the soil was kept at 30 per cent or at 15 per cent moisture, but the fertilizers applied gave marked differences. On the unfertilized soils the phosphoric acid was decidedly lower than where fertilizers were applied, and the complete fertilizer gave higher results than did high nitrogen. It is difficult to see the reason for this last condition, since there was as much phosphate applied with the high nitrogen as with the complete fertilizer; and why merely an excess of nitrate should diminish the phosphate dissolved is not clear.

EFFECTS ON THE GROWTH AND MORPHOLOGY OF WHEAT

Length of periods of growth

A record was kept of the following periods of growth in the life of the plants under different treatments: (1) number of days from planting to heading; (2) number of days from heading to maturity; (3) number of days from planting to maturity; (4) duration of the period of heading, from the time when the first head appeared in a pot until the last head was visible.

The method of obtaining these data accurately was as follows: When the plants began to head they were examined carefully every day. The

heads that had appeared since the last examination were marked and the date was recorded; when the heading of any pot was complete, the sum of the total days from the time of planting until each head appeared was divided by the number of heads. This gave the average for each pot. The period of ripening was obtained in the same way, and from these data the results given below were calculated. The period of ripening was not determined during 1908–1909.

TABLE 19. EFFECT OF HIGH AND OF LOW MOISTURE AT DIFFERENT STAGES OF GROWTH ON THE LENGTH OF THE VARIOUS GROWING PERIODS IN WHEAT. AVERAGE FOR ALL FERTILIZER TREATMENTS. RESULTS FOR TWO YEARS

Number of pots	Percentage of soil moisture			Average number of days from planting to heading		Days from heading to maturity, 1909–1910	Days from planting to maturity, 1909–1910	Duration of heading period (days)	
	First stage	Second stage	Third stage	1908–1909	1909–1910			1908–1909	1909–1910
6.....	30	30	30	173.3	161.0	47.3	208.3	18.7	19.3
6.....	30	30	15	172.7	160.6	44.7	205.3	20.0	21.0
6.....	30	15	15	170.0	157.0	47.0	204.0	18.3	21.7
6.....	15	15	15	182.3	164.0	48.3	212.3	22.0	20.0
6.....	15	15	30	180.0	161.3	53.4	214.7	31.0	21.7
6.....	15	30	15	176.7	162.0	45.7	207.7	17.7	19.3

On examining the number of days from planting to heading, it will be seen that this period was longer in every case during 1908–1909 than during 1909–1910. The plants receiving low moisture all the time were slowest to head, while those receiving high moisture up to the five-leaf stage, and low moisture all the time after that stage, were first to head during both years. Lowering the moisture at the end of the first stage hastened heading more than did lowering it at any other time or keeping it high. Raising the moisture from low to high at the five-leaf stage hastened heading somewhat, even though the moisture was again lowered at the boot stage.

The period from heading to maturity was not so much affected by the change in moisture as was that from planting to heading. However, changing the soil moisture from high to low at the boot stage cut this period short, while changing it from low to high at the same time decidedly lengthened the period.

When the total time from planting to maturity is considered, nearly the same relation is seen to exist as in the period from planting to heading. One very noticeable difference, however, is seen in the pots that had received 15 per cent moisture up to the end of the second period but were given 30 per cent during the third period. The effect of this additional water seems to have been to hasten heading slightly, but to retard ripen-

ing — as if the plants had gained a new lease on life and desired to store up more material before completing their life's work. Even at this late stage the plants sent out new shoots and became decidedly greener than those that remained dry. A difference of more than ten days will be seen in the period of ripening of two treatments, depending entirely on when they received their high moisture. Both received 15 per cent moisture during two periods and 30 per cent during one; but high moisture at first and low later hastened maturity, while the reverse condition retarded it.

In regard to the duration of heading, or the length of time after heading began in a pot until it was completed, there was much greater variation during 1908–1909 than during 1909–1910. However, the difference between the years is more quantitative than qualitative. When the moisture was raised at the boot stage the period of heading was longest; and when it had been high during the second stage but was lowered at the beginning of the third stage, heading did not continue so long. This is exactly what might be expected.

TABLE 20. Effect of Different Soil Moisture Contents on the Length of the Various Growing Periods in Wheat. Unfertilized Soil. 1909–1910

Number of pots	Soil moisture (percentage)	Days from planting to heading	Days from heading to maturity	Days from planting to maturity	Duration of heading period (days)
2	11	175	49	224	22
2	13	170	51	221	19
2	20	159	49	208	19
2	25	159	50	209	18
2	37½	166	48	214	21
2	45	179	45	224	25

On examining Table 20 it is seen that the very dry as well as the very wet soil increased all the periods of growth over the soil of medium moisture except the period from heading to maturity. The plants receiving 20 per cent moisture headed twenty days earlier than those receiving 45 per cent, and the duration of the heading period was six days less. The average date of maturity was exactly the same for 11 per cent moisture (which was as dry a soil as would allow the plants to grow) as for 45 per cent (when the soil was completely saturated, with considerable free water in the bottom of the pot).

The results given in Table 21 show that fertilizers hastened the time of heading, the complete fertilizer usually being more effective than

TABLE 21. EFFECT OF FERTILIZERS ON THE LENGTH OF THE VARIOUS PERIODS OF GROWTH IN WHEAT. AVERAGES FOR ALL MOISTURE TREATMENTS. RESULTS FOR TWO YEARS

Fertilizer	Number of pots	Days from planting to heading		Days from heading to maturity	Days from planting to maturity	Duration of heading period (days)	
		1908–1909	1909–1910	1909–1910	1909–1910	1908–1909	1909–1910
None	12	179.7	167	47.3	214.3	19.5	20.1
Complete	12	172.7	158	47.5	205.5	20.2	20.8
High nitrogen	12	175.1	158	49.1	207.1	24.2	20.5

high nitrogen. The same relation exists with the total period of growth. Where no fertilizers were added, the plants matured nine days later than with complete fertilizer and seven days later than with high nitrogen. The duration of the heading period was always lengthened by the fertilizers. The general conclusion might be drawn that an evenly balanced fertilizer tended to make the plants mature in the shortest time, and even a high nitrogen fertilizer made the period shorter than where no fertilizer was applied.

Tillering

Counts were made at various periods during the growth of the plants, in order to determine the amount of tillering, or stooling. It will be remembered that there were originally but twelve plants in each pot, so that any above this number resulted from branching, or tillering. Of course most of the branching was at the base of the culm, but there was also considerable tendency for the culm to branch at the top node, thus producing two or three heads on one culm. This was especially true during 1908–1909 and with certain treatments.

In Tables 22 and 23 it is shown how the number of tillers varied as the plants grew.

In Table 22 it is seen that there were always more tillers with 30 per cent than with 15 per cent soil moisture; also that, as a rule, the fertilized pots, and especially those with high nitrogen, had more tillers than did the unfertilized pots.

In comparing the seasons, the crop grown during 1909–1910 tillered more with every treatment than did that grown during 1908–1909. This may be due in part to the different conditions during the two years; but it is more probably due mainly to the variety of wheat, Pringle's Champion tillering less than Galgalos.

TABLE 22. NUMBER OF TILLERS AT VARIOUS STAGES WITH DIFFERENT FERTILIZERS AND WITH HIGH AND LOW MOISTURE. RESULTS FOR TWO YEARS

Soil moisture (percentage)	Fertilizer	Average number of tillers per pot					
		1908–1909			1909–1910		
		First stage	Second stage	Number of heads at maturity	First stage	Second stage	Number of heads at maturity
30	None	29.6	13.5	15.5	39.5	15.5	16.5
15	None	12.0	12.0	12.0	19.5	13.5	13.5
30	Complete	39.6	17.0	19.0	43.0	21.5	22.0
15	Complete	18.2	12.0	12.0	29.5	16.0	16.5
30	High nitrogen	42.6	17.0	19.0	45.0	23.5	26.5
15	High nitrogen	14.2	11.5	13.0	31.5	15.5	15.0

TABLE 23. NUMBER OF TILLERS AT VARIOUS STAGES WITH WIDELY VARYING SOIL MOISTURE. NO FERTILIZER. 1909–1910

Soil moisture (percentage)	Average number of tillers per pot		
	First stage	Second stage	Number of heads at maturity
11	13.0	12.0	12.0
13	15.0	12.0	12.0
15	19.5	13.5	13.5
20	17.5	12.0	12.5
25	24.0	14.5	14.5
30	39.5	15.5	16.5
$37\frac{1}{2}$	33.0	18.0	18.5
45	31.0	22.5	20.0

With some of the treatments there were more than twice as many tillers at the five-leaf stage as at the boot stage, the others having died. This falling off in the number of tillers was greater with the higher percentage of moisture.

What seems to be a rather peculiar condition is that actually more heads were produced than were tillered at the boot stage. This was due to a branching of the culm at the top node, and the production of secondary heads which usually matured somewhat later than the first heads.

In Table 23 it will be noticed that 30 per cent moisture produced the most tillers at first, but that 45 per cent moisture gave the most heads

at maturity. With the low amounts of moisture there was scarcely any stooling. The relation between the periods is similar to that found in Table 22.

TABLE 24. EFFECT OF HIGH AND OF LOW MOISTURE AT DIFFERENT STAGES ON THE NUMBER OF HEADS OF WHEAT PRODUCED PER POT. AVERAGE FOR ALL FERTILIZER TREATMENTS. RESULTS FOR TWO YEARS

Number of pots	Percentage of soil moisture			Average number of heads per pot	
	First stage	Second stage	Third stage	1908–1909	1909–1910
6	30	30	30	17.8	21.7
6	30	30	15	15.7	20.7
6	30	15	15	14.2	17.8
6	15	15	15	12.3	15.0
6	15	15	30	14.3	15.7
6	15	30	15	13.8	18.2

The fact previously noted, that more tillers were produced during 1909–1910 than during 1908–1909 is shown also in this table. The greatest number of heads was produced when there was 30 per cent moisture throughout the entire growth of the plants, and the least number when there was 15 per cent all the time. Raising the moisture during any period increased the number of heads, while lowering it at any time had the opposite effect.

TABLE 25. EFFECT OF FERTILIZERS ON THE NUMBER OF HEADS PER POT. AVERAGE FOR ALL MOISTURE TREATMENTS. RESULTS FOR TWO YEARS

Fertilizer	Number of pots	Average number of heads per pot	
		1908–1909	1909–1910
None	12	13.3	15.1
Complete	12	15.1	19.4
High nitrogen	12	15.7	20.0

This summary table shows what has been previously noted; namely, that the fertilizers, and especially those with high nitrogen, increased tillering and the production of heads.

Miscellaneous observations and measurements during growth

General observations.— Within two or three weeks after the plants were up, they began to show distinct response to the fertilizers and moisture.

Those with 30 per cent moisture showed a darker color, broader leaves, and a more thrifty appearance generally, than those with 15 per cent. The fertilized plants showed similar advantages over the unfertilized ones.

When the soil moisture was changed from 30 per cent to 15 per cent in the pots at any stage, the plants very soon lost their turgor and looked wilted, and it was a number of weeks before they seemed to regain equilibrium. They also became covered with a white waxy bloom, so that the plants receiving this treatment could be readily distinguished from the others. All the plants took on this bloom, to an extent, later.

In the pots in which the moisture content was changed from 15 to 30 per cent at the end of the first or the second stage, an increased vigor of growth was noticeable within a week or two. This newer, rapid growth was lighter in color than the old, slower growth.

During most of the life of the wheat plants there were but five green leaves at a time on each culm. As fast as a new leaf was formed an old one died. The treatment affected the rate at which the new leaves were formed; but the number of green leaves was practically constant until the plants approached maturity, when the number was reduced. The plants in the drier soil remained green longer than did those in the wet soil.

Mildew, which attacked the plants from time to time, seemed to be severer on the plants with high moisture, and especially on those with high nitrogen fertilizer. The plants with 30 per cent moisture and with high nitrogen also had weaker culms than did those receiving other treatments, and when the supports were removed these plants were unable to support their own weight.

Until the end of the first month the plants in the soil with 45 per cent moisture were the tallest; after that they fell behind those in the soil with $37\frac{1}{2}$ per cent moisture. These in turn remained the tallest for about two months, when even they fell behind those on the soil with 25 per cent moisture. Thus the plants did not respond in the same relation to soil moisture during all periods of growth. They seemed able to endure more moisture during early periods than later.

Measurements at the end of the first period.— The relative heights of plants with different treatments is shown in Table 26.

The striking fact shown in Table 26 is that with the variety of wheat grown in 1909–1910 the height was not so much affected by the various treatments as with the variety grown in 1908–1909. However, the weight of dry matter at maturity showed the effects much more than the above measurements would indicate.

Measurements at the end of the second period.— The relative size of the plants at the boot stage is brought out in Tables 27 and 28.

TABLE 26. EFFECT OF MOISTURE AND OF FERTILIZERS ON HEIGHT OF WHEAT PLANTS AT THE FIVE-LEAF STAGE. RESULTS FOR TWO YEARS

Fertilizer	Soil moisture (percentage)	Number of pots	Average height of plants (inches)	
			1908–1909	1909–1910
None	30	6	17.0	10.5
None	15	6	7.5	8.5
Complete	30	6	22.0	13.0
Complete	15	6	14.0	10.0
High nitrogen	30	6	24.0	13.0
High nitrogen	15	6	16.0	11.0

TABLE 27. EFFECT OF MOISTURE AND OF FERTILIZERS ON THE HEIGHT, LEAF LENGTH, AND LEAF WIDTH OF WHEAT PLANTS AT THE BOOT STAGE. RESULTS FOR TWO YEARS

Percentage of soil moisture		Fertilizer	Number of tops	Average height to base of top leaf (inches)		Average length of second leaf from top (inches)		Average width of second leaf from top (centimeters)	
First stage	Second stage			1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910
30	30	None	4	19.0	11.5	11.5	7.0	1.2	0.9
30	15	None	2	18.0	11.0	10.0	5.0	1.1	0.9
15	15	None	4	8.5	11.0	9.0	7.5	0.6	0.8
15	30	None	2	12.0	13.0	12.0	10.0	1.1	0.9
30	30	Complete	4	24.5	22.0	12.0	8.5	1.2	1.0
30	15	Complete	2	24.0	20.0	10.5	8.0	1.2	0.9
15	15	Complete	4	15.0	15.0	10.0	8.0	0.9	0.9
15	30	Complete	2	21.0	21.0	14.5	9.0	1.2	1.0
30	30	High nitrogen	4	29.0	25.5	13.0	11.0	1.3	1.1
30	15	High nitrogen	2	24.0	23.0	11.0	9.0	1.1	1.0
15	15	High nitrogen	4	13.0	18.0	10.5	9.0	0.9	0.9
15	30	High nitrogen	2	24.0	20.0	15.5	12.0	1.4	1.0

On examining Table 27 it is seen that the measurements for height at the end of the second period continued in about the same relation as those shown in Table 26 for the first stage. The differences between the treatments, however, are not so marked. When the moisture was lowered from 30 to 15 per cent at the end of the first period, the height, the leaf length, and the leaf width were all lessened in comparison to the plants receiving 30 per cent during both periods. When the moisture was raised from 15 to 30 per cent at this stage, however, there was a decided increase in all these measurements, the leaf length being the most affected. In every case a longer leaf was produced by this treatment than by any

TABLE 28. EFFECT OF A WIDE RANGE OF SOIL MOISTURE ON THE HEIGHT, LEAF LENGTH, AND LEAF WIDTH OF WHEAT PLANTS AT THE BOOT STAGE. 1909–1910

Soil moisture (percentage)	Average height to base of top leaf (inches)	Average length of second leaf from top (inches)	Average width of second leaf from top (centimeters)
11	9	7	0.6
13	10	8	0.7
20	15	9	0.8
25	18	8	0.9
37½	17	9	1.0
45	11	8	0.7

other. It will be noted that when the moisture was low during both periods, the width of the leaves was especially small.

The degree to which the extremes of moisture affected the various measurements is shown in Table 28. At the boot stage the highest plants were those receiving 25 per cent moisture; while the very moist, as well as the very dry, soil produced shorter plants. The length of leaf was not so much affected as was the width, which was nearly twice as great with 37½ per cent moisture as with the very dry soil. The plants grown with 45 per cent moisture were about the same size as those with but 13 per cent, while during the first month of growth they were better than the plants with any other treatment.

Morphology at maturity

At the time of harvest detailed measurements were made, and these are summarized in the tables that follow.

TABLE 29. EFFECT OF DIFFERENT SOIL MOISTURE CONTENTS ON THE NUMBER OF NODES PER CULM, LENGTH OF CULM, LENGTH OF HEAD, AND RATIO OF CULM LENGTH TO HEAD LENGTH. NO FERTILIZER. 1909–1910

Soil moisture (percentage)	Number of pots	Average number of nodes per culm	Average length of culm (inches)	Average length of head (inches)	Ratio of culm length to head length
11	2	3.8	16.7	1.45	11.5:1
13	2	3.7	18.9	1.60	11.8:1
20	2	3.5	26.4	2.25	11.7:1
25	2	3.8	29.2	2.20	13.3:1
37½	2	4.1	31.1	2.30	13.5:1
45	2	4.4	22.8	1.75	13.0:1

The very wet soil produced culms with the greatest number of nodes, while the medium degree of moisture produced the least number of nodes.

The largest culms and heads were produced with $37\frac{1}{2}$ per cent moisture, while with 45 per cent the culms and heads were shorter than in any other except the very dry soil. Thus, similarly to too little moisture, too much moisture retarded the growth. When the ratio of the culm length to the head length is examined, it is seen that the drier soils produced proportionately longer heads than did the moist soils.

The number of nodes per culm does not vary greatly with changes in moisture; but, as is seen in Table 30, the difference between the two

TABLE 30. EFFECT OF HIGH AND OF LOW MOISTURE DURING DIFFERENT PERIODS OF GROWTH ON THE NUMBER OF NODES PER CULM, LENGTH OF CULM, LENGTH OF HEAD, AND RATIO OF CULM LENGTH TO HEAD LENGTH. AVERAGE FOR ALL FERTILIZER TREATMENTS. RESULTS FOR TWO YEARS

Percentage of soil moisture			Number of pots	Average number of nodes per culm		Average length of culm (inches)		Average length of head (inches)		Ratio of culm length to head length	
First stage	Second stage	Third stage		1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910
30	30	30	6	5.9	3.9	38.7	33.0	2.93	2.38	13.2 : 1	13.9 : 1
30	30	15	6	5.9	3.9	35.6	29.6	2.80	2.35	12.7 : 1	12.6 : 1
30	15	15	6	6.3	3.9	35.8	29.4	2.60	2.63	13.8 : 1	11.2 : 1
15	15	15	6	5.7	3.6	26.0	26.0	1.97	2.22	13.2 : 1	11.7 : 1
15	15	30	6	5.3	3.7	28.5	29.8	2.47	2.45	11.5 : 1	12.2 : 1
15	30	15	6	5.2	3.7	32.6	28.3	2.77	2.33	11.8 : 1	12.1 : 1

seasons is very marked, due, no doubt, to the variety used. The figures bring out distinctly that the number of nodes per culm is largely determined by the moisture present during the first period of growth. When there was 30 per cent moisture at first the number was always greater than when there was 15 per cent, regardless of later treatment.

The length of the culm also seemed to be more influenced by the moisture during the first period than at any other time. However, raising the moisture in any other period also increased the length, while lowering it had the opposite effect; and, in most cases, where the moisture was high during two periods, the culms were longer than where it was high during but one period.

The shortest heads were always produced where the moisture was low all the time. Raising the moisture during any period increased the length of the head.

The difference between the number of nodes per culm in the two varieties is shown distinctly in Table 31. The table brings out also the fact that the number of nodes was greater on the fertilized soil, especially where

high nitrogen was used. The length of the culms and of the heads was also greater where fertilizers were applied. The length of the heads in comparison with the culms, however, was proportionately greater in the unfertilized than in the fertilized crop.

TABLE 31. EFFECT OF FERTILIZERS ON THE NUMBER OF NODES PER CULM, LENGTH OF CULM, LENGTH OF HEAD, AND RATIO OF CULM LENGTH TO HEAD LENGTH. AVERAGE FOR ALL MOISTURE TREATMENTS. RESULTS FOR TWO YEARS

Fertilizer	Number of pots	Average number of nodes per culm		Average length of culm (inches)		Average length of head (inches)		Ratio of culm length to head length	
		1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910
None	12	5.5	3.5	29.8	24.8	2.43	2.13	12.3:1	11.6:1
Complete	12	5.7	3.9	34.7	30.1	2.75	2.40	12.6:1	12.5:1
High nitrogen	12	6.0	3.9	34.1	33.2	2.59	2.68	13.2:1	12.4:1

Number, weight, and kind of kernels

A count was made of the kernels produced in each pot, and, since the number of heads was known, it was easy to determine the average number of kernels produced per head. The air-dry kernels were also weighed, and the weight of one hundred kernels was calculated from the total number and the total weight.

TABLE 32. EFFECT OF DIFFERENT MOISTURE CONTENTS ON THE NUMBER OF KERNELS PER POT, NUMBER OF KERNELS PER HEAD, AND WEIGHT OF 100 KERNELS. NO FERTILIZER. 1909–1910

Soil moisture (percentage)	Number of pots	Average number of kernels per pot	Average number of kernels per head	Weight of 100 kernels (grams)
11	2	59	4.9	3.89
13	2	68	5.7	4.09
15	2	112	8.3	3.83
20	2	138	11.1	3.64
25	2	160	11.1	3.60
30	2	148	9.0	3.88
$37\frac{1}{2}$	2	201	10.9	3.32
45	2	170	8.4	3.05

The number of kernels produced in a single pot increased with an increase in moisture up to $37\frac{1}{2}$ per cent, but above that amount it decreased. The number of kernels per head was greater with a medium amount of

moisture than with very little or very much. In general, however, the low moisture produced heads containing fewer kernels than those produced by the high moisture.

As to the plumpness of grain and the weight of one hundred kernels, the results are quite different. The largest, plumpest, and heaviest kernels were produced with very low moisture, and the lightest with very high. Indeed, the kernels from the soil with 45 per cent moisture were considerably shrunken. This was not due to any cutting short of the growing period or sudden unfavorable condition at the last, for the plants had a normal maturation and a long period of growth.

An examination of the kernels showed that those grown with very low moisture were practically all flinty and hard in appearance, with a light reddish tint; and that as the moisture increased the number of flinty kernels decreased, until with $37\frac{1}{2}$ per cent moisture there were no flinty kernels but all had a starchy appearance. This plumpness of kernels should be compared with the percentage of nitrogen given later.

The following table shows, in general, the most kernels, per pot as well as per head, where the moisture was high, and the least number where the moisture was low, during the entire period of growth. Where there

TABLE 33. EFFECT OF HIGH AND OF LOW MOISTURE DURING DIFFERENT PERIODS OF GROWTH ON THE NUMBER OF KERNELS PER POT, NUMBER OF KERNELS PER HEAD, AND WEIGHT OF 100 KERNELS. AVERAGE FOR ALL FERTILIZER TREATMENTS. RESULTS FOR TWO YEARS

Percentage of soil moisture			Number of pots	Average number of kernels per pot		Average number of kernels per head		Average weight of 100 kernels (grams)	
First stage	Second stage	Third stage		1908 1909	1909-1910	1908-1909	1909-1910	1908-1909	1909-1910
30	30	30	6	406	297	23	13.2	2.73	3.72
30	30	15	6	336	237	22	11.1	2.83	4.07
30	15	15	6	255	225	19	12.5	2.85	3.84
15	15	15	6	159	153	13	10.2	2.80	3.78
15	15	30	6	288	211	20	13.6	2.81	3.78
15	30	15	6	289	217	21	11.9	2.86	3.86

was low moisture during two periods and high during one, it did not seem to matter greatly which period received the high moisture. During 1908 1909 the number of kernels, per pot as well as per head, was much more affected by the moisture than during 1909-1910. The number of kernels was greater during 1908-1909 than during 1909-1910, but the grain produced in the latter year was decidedly the heavier. The weight of one hundred kernels was always greater where the moisture was changed at some period than where it remained at either 30 per cent or 15 per cent all the time. The lighter kernels were associated with the higher moisture.

TABLE 34. EFFECT OF FERTILIZERS ON THE NUMBER OF KERNELS PER POT, NUMBER OF KERNELS PER HEAD, AND WEIGHT OF 100 KERNELS. AVERAGE FOR ALL MOISTURE TREATMENTS. RESULTS FOR TWO YEARS

Fertilizer	Number of pots	Average number of kernels per pots		Average number of kernels per head		Average weight of 100 kernels (grams)	
		1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910
None	12	230	141	17	10	2.81	3.94
Complete	12	318	230	21	12	2.84	3.82
High nitrogen	12	319	299	20	15	2.79	3.77

In Table 34 it is seen that the fertilized soils produced more kernels, per pot and per head, than did the unfertilized. The high nitrogen was on the average more effective in this regard than the balanced complete fertilizer. The lightest grain was produced by the high nitrogen fertilizer, and, as a rule, the heaviest grain came from the unfertilized soil.

From the results shown in the last three tables, it would appear that certain of the conditions favoring the production of but few kernels tend to produce heavy, plump grain. It seems that the wheat plant responds to unfavorable conditions by diminishing the number of kernels produced, rather than by decreasing the size and weight of the kernels.

EFFECTS ON YIELD

Dry matter produced at different stages

During the season of 1908–1909, plants were harvested at the boot and at the bloom stage as well as at maturity. The roots for all plants raised during this season were carefully weighed and analyzed. During the season of 1909–1910 no harvests were made except at maturity and no roots were washed out, since it was desired to make a more careful study of the soil.

From a study of Table 35 it is seen that the dry matter in the tops rapidly increased from the boot stage to maturity. With the high moisture there was more than twice as much at the latter period as at the former, while with low moisture the increase was not so great. In other words, proportionately more of the dry matter in the tops was produced by the boot stage in the dry soil than was produced in the wet.

The weight of roots recovered decreased from the boot stage to maturity, with all treatments. This may have been due to an actual dying and decaying of some of the roots as the plants approached maturity, or it may have been due to the fact that all the roots could not be so well

TABLE 35. EFFECT OF MOISTURE AND OF FERTILIZERS ON THE DRY WEIGHT OF TOPS AND ROOTS OF WHEAT AT VARIOUS STAGES OF GROWTH. 1908–1909

Fertilizer	Soil moisture (percentage)	Dry weight of tops (grams)			Dry weight of roots (grams)			Ratio of tops to roots		
		Boot stage	Bloom stage	Maturity	Boot stage	Bloom stage	Maturity	Boot stage	Bloom stage	Maturity
None	30	35.31	50.54	74.95	15.80	10.73	9.31	2.2:1	4.7:1	8.1:1
None	15	15.21	19.38	29.28	10.02	8.82	9.59	1.5:1	2.2:1	3.1:1
Complete	30	45.48	76.24	102.02	22.87	14 36	11.71	2.0:1	5.3:1	8.7:1
Complete	15	27.79	39.96	52.32	20.76	12.46	13.19	1.3:1	3.2:1	4.0:1
High nitrogen	30	39.69	65.97	112.12	14.13	12.65	11.45	2.8:1	6.1:1	9.8:1
High nitrogen	15	26.50	39.47	37.78	18.29	11.40	13.19	1.4:1	3.5:1	2.9:1

recovered when the plants were older. In the unfertilized soil and in that receiving complete fertilizer, the weight of roots was greater in the moist soil at the bloom and boot stages than in the dry soil, while at maturity just the opposite was true. In the soil receiving high nitrogen, however, the dry soil contained actually more roots than the moist, notwithstanding the fact that the wet soil produced about three times as much top as did the dry soil. This is brought out when the ratio of the tops to the roots is studied.

In all treatments there were proportionately more tops as the plants matured. Likewise at all stages the relative weight of tops was greater in the moist than in the dry soil, and greater in the fertilized than in the unfertilized soil.

Dry matter at maturity

The yields of grain and of straw increased regularly with the moisture up to 37½ per cent, but at 45 per cent the yield of both, and especially that of the grain, was considerably reduced.

TABLE 36. EFFECT OF DIFFERENT SOIL MOISTURE CONTENTS ON THE DRY WEIGHT OF GRAIN AND STRAW. NO FERTILIZER. 1909–1910

Soil moisture (percentage)	Weight per pot (in grams)			
	Grain	Straw	Grain and straw	Ratio of straw to grain
11	4.07	11.06	15.13	2.72:1
13	4.96	12.96	17.92	2.61:1
15	7.68	18.80	26.48	2.45:1
20	8.97	21.15	30.12	2.36:1
25	10.30	25.17	35.47	2.44:1
30	10.32	26.90	37.22	2.61:1
37½	13.73	34.70	48.43	2.53:1
45	9.17	27.27	36.44	2.97:1

The largest relative amount of grain was produced with an intermediate soil moisture with respect to both the very dry and the very wet, the latter especially producing proportionately more straw.

TABLE 37. EFFECT OF HIGH AND OF LOW MOISTURE DURING DIFFERENT PERIODS OF GROWTH ON THE DRY WEIGHT OF GRAIN, STRAW, AND ROOTS OF WHEAT. AVERAGE FOR ALL FERTILIZER TREATMENTS. RESULTS FOR TWO YEARS

Percentage of soil moisture			Number of pots	Weight per pot (in grams)						Ratio of straw to grain		Weight of roots (grams)	Ratio of tops to roots
				Grain		Straw		Grain and straw					
First stage	Second stage	Third stage		1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1908–1909
30	30	30	6	9.94	9.80	34.94	23.23	44.88	33.03	3.5 : 1	2.4 : 1	5.41	9.1 : 1
30	30	15	6	8.55	8.68	31.98	21.39	40.53	30.07	3.7 : 1	2.5 : 1	6.76	6.1 : 1
30	15	15	6	8.24	7.69	26.40	18.74	34.64	26.43	3.2 : 1	2.4 : 1	6.06	5.9 : 1
15	15	15	6	4.14	5.17	15.75	12.88	19.89	18.05	3.8 : 1	2.5 : 1	5.99	3.3 : 1
15	15	30	6	7.25	7.06	20.66	14.96	27.91	22.02	2.8 : 1	2.1 : 1	5.73	5.0 : 1
15	30	15	6	7.38	7.47	25.81	17.97	33.19	25.44	3.5 : 1	2.4 : 1	8.58	3.8 : 1

From Table 37 it is seen that the greatest quantity of grain, as well as of straw, was always produced on the soil receiving 30 per cent moisture during the three periods, while the least quantity was produced on that receiving 15 per cent. Raising the moisture during any period increased the yield of both grain and straw, and having the moisture high during two periods increased the yield still more. The fact that the grain and the straw were not affected to the same degree by these changes in moisture is clearly brought out in the figures for ratio of straw to grain. Where the soil humidity was maintained at 30 per cent or at 15 per cent during all periods there was nearly four times as much straw as grain in 1908–1909, but raising or lowering the humidity at any time affected this ratio. The treatment giving relatively most grain was that in which the moisture was kept at 15 per cent during the first two periods but raised to 30 per cent during the third; while in the treatment giving relatively least grain the moisture was kept at 15 per cent during the entire growth of the crop. Those pots receiving high moisture at first and low moisture later always produced proportionately more straw than those receiving low moisture at first and high moisture later.

The weight of roots was least in the soil receiving 30 per cent moisture continuously, and greatest in that with 15 per cent in the first and third periods and 30 per cent in the second period.

The ratio of tops to roots was very much affected by the moisture treatment, being nearly three times as great in the moist as in the dry soil. The moisture received during early periods of growth was more important in influencing this ratio than that received later.

The effects of fertilizers on the yield of the various parts of the plant are summarized in the following table:

TABLE 38. EFFECT OF FERTILIZERS ON THE DRY WEIGHT OF GRAIN, STRAW, AND ROOTS OF WHEAT. AVERAGE FOR ALL MOISTURE TREATMENTS. RESULTS FOR TWO YEARS

Fertilizer	Number of pots	Weight per pot (in grams)						Ratio of straw to grain		Weight of roots (grams)	Ratio of tops to roots
		Grain		Straw		Grain and straw					
		1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1908–1909
None	12	5.72	4.94	20.61	12.00	26.33	16.94	3.6 : 1	2.4 : 1	5.91	4.7 : 1
Complete	12	8.06	7.85	29.84	19.11	37.90	26.96	3.7 : 1	2.4 : 1	6.53	6.1 : 1
High nitrogen	12	8.04	10.12	29.92	23.47	37.96	33.59	3.7 : 1	2.3 : 1	6.83	5.9 : 1

The fertilized soil always gave a better yield of each of the plant parts than did the unfertilized. In 1908–1909 the complete fertilizer and that with high nitrogen gave about the same yield of grain, straw, and roots; but in 1909–1910 the high nitrogen proved superior. The data are not given here in sufficient detail to bring out one point that was constantly noticed, namely, that the high nitrogen fertilizer was more efficient in the soil with high moisture than in that with low moisture.

The ratio of straw to grain was not, on the average, greatly affected by the fertilizers, but under certain moisture conditions there was a decided effect.

The actual weight of roots was greater in the fertilized pots, but compared with the tops the unfertilized soil produced more roots. These results and those previously cited show that the root growth is relatively greater in soils lacking fertility and in those containing low moisture. This is in agreement with the findings of the investigators mentioned in the summary of the literature on the subject.

EFFECTS ON TRANSPIRATION

The transpiration was accurately determined by the method previously described. Weighings were made at the same hour at the end of each week, so that the transpiration by weeks could be obtained. The results for total transpiration and the relation between water transpiration and dry matter produced will first be discussed.

Total transpiration, and relation between transpiration and dry matter produced

In Table 39 it is seen that the transpiration is least in the driest soil, that it gradually rises with the soil moisture up to $37\frac{1}{2}$ per cent, and that it then falls off; and that with 45 per cent moisture the transpiration is but slightly greater than with 25 per cent. The relative economy of transpiration shown in the last two columns brings out some interesting relations. The greatest economy in the production of total dry matter was

TABLE 39. EFFECT OF DIFFERENT SOIL MOISTURE CONTENTS ON THE TOTAL WATER TRANSPIRED BY WHEAT AND ON THE AMOUNT OF WATER TRANSPIRED IN PRODUCING A UNIT OF DRY MATTER. NO FERTILIZER. 1909–1910

Soil moisture (percentage)	Number of pots	Total transpiration per pot (kilograms)	Number of grams of water transpired in producing one gram of straw and grain	Number of grams of water transpired in producing one gram of grain
11	2	5.58	737	2,743
13	2	6.78	696	2,740
20	2	11.27	739	2,690
25	2	14.37	811	2,793
$37\frac{1}{2}$	2	20.67	854	3,010
45	2	15.42	850	3,369

with 13 per cent soil moisture, but the grain was most economically produced with 20 per cent. Less economy is found in both cases with very high moisture. The results indicate that dry matter can be produced with the greatest economy of water on a medium dry soil, but if the soil is very dry or very wet there is more waste. This waste in water is particularly noticeable with very high moisture. A number of investigators have reported that they found no relation between soil humidity and the water required in order to produce a unit of dry weight. It is likely, however, that they did not test enough points between the high and the low moisture to show the real condition. A high and a low moisture might give the same result, while an intermediate degree would give a different result.

A study of Table 40 shows that, as might be expected, the greatest total transpiration was with the high moisture during all three periods, and the least was with the low moisture during the entire time of growth. High moisture during the second period increased the transpiration more

than during any other single period. This was doubtless due to the fact that this was the period of most rapid growth.

TABLE 40. EFFECT OF HIGH AND OF LOW SOIL MOISTURE DURING DIFFERENT PERIODS OF GROWTH ON THE TOTAL TRANSPIRATION OF WHEAT AND ON THE AMOUNT OF WATER TRANSPIRED IN PRODUCING A UNIT OF DRY MATTER. AVERAGE FOR ALL FERTILIZER TREATMENTS. RESULTS FOR TWO YEARS

Percentage of soil moisture			Number of pots	Total transpiration per pot (kilograms)		Number of grams of water transpired in producing one gram of straw and grain		Number of grams of water transpired in producing one gram of grain	
First stage	Second stage	Third stage		1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910
30	30	30	6	30.13	22.98	626	739	3,066	2,553
30	30	15	6	22.88	19.59	568	682	2,689	2,428
30	15	15	6	17.31	15.10	502	601	2,636	2,166
15	15	15	6	10.25	11.53	529	653	2,597	2,280
15	15	30	6	15.97	15.13	576	698	2,230	2,194
15	30	15	6	17.58	16.20	532	643	2,397	2,199

The greatest waste of water in the production of grain and straw, as well as of grain alone, was always in the pots receiving 30 per cent moisture during all three periods.

Considering both straw and grain, the most economical treatment was with 30 per cent moisture during the first period and 15 per cent during the last two periods. Considering grain alone, however, it was more economical to have the high moisture come later. In 1908–1909, 37 per cent more water was required in order to produce the dry matter in grain where there was high moisture continuously than where there was high moisture only during the last stage. This is certainly an important economic difference where water is the limiting factor in plant growth and where the time of application can be regulated by irrigation. The difference between these treatments was of considerable importance. These results point very strongly to the fact that the time when water is applied has a great influence on the quantity of dry matter that a given quantity of water will produce.

Fertilizers greatly increased the transpiration, and the high nitrogen caused a greater transpiration than did the complete fertilizer. This was especially the case in the presence of high moisture. The table above is not given in sufficient detail to show this fact.

When the relation between transpiration and dry matter is examined, it is seen that water was not used so economically by the unfertilized as by the fertilized soil. During the season of 1909–1910 the high nitrogen fertilizer was much more economical in its use of water than the complete

TABLE 41. EFFECT OF FERTILIZERS ON THE TOTAL TRANSPIRATION OF WHEAT AND ON THE AMOUNT OF WATER TRANSPIRED IN PRODUCING A UNIT OF DRY MATTER. AVERAGE FOR ALL MOISTURE TREATMENTS. RESULTS FOR TWO YEARS

Fertilizer	Number of pots	Total transpiration per pot (kilograms)		Number of grams of water transpired in producing one gram of straw and grain		Number of grams of water transpired in producing one gram of grain	
		1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910
None	12	15.50	13.23	583	781	2,641	2,711
Complete	12	20.58	17.22	533	634	2,522	2,186
High nitrogen	12	20.98	19.82	551	593	2,678	1,976

fertilizer, but during the previous year the result was slightly in favor of the complete fertilizer. The results all the way through indicate that a given quantity of water will produce more dry matter on a fertile than on an unfertile soil.

The above data make it very clear that a pound of dry matter in wheat does not always require the same amount of water for its production, as was believed by some of the early workers. The results of a number of investigators already referred to show that conditions modify this relation. This line of investigation, if pursued further and applied practically to regions where moisture is the chief consideration in crop production, would be of the greatest economic importance.

Transpiration during various periods of growth

The relative transpiration during the various periods of growth was determined; but, since some of this work has been presented elsewhere by the author (1911), its discussion here will be confined to a few general statements. The transpiration, small at first, gradually increased until after the plants had blossomed, when it rapidly diminished, and as maturity was approached there was scarcely any water transpired. This is shown in the curve that follows (Fig. 108). The irregularities in the transpiration in response to external conditions will be discussed later.

It was found that the quantitative relation between the transpiration for different treatments did not continue the same at all times; that is, at the end of one month the relative transpiration was not the same as at the end of two or three months or at maturity. Those wishing to investigate this question further will find it discussed in some detail in the paper just referred to.

Relation of transpiration to temperature, sunshine, and humidity

An effort was made to keep the temperature of the greenhouse between 60° and 65° F. It was impossible to do this completely, but a thermographic record was kept, so that all fluctuations are known. The relative humidity was determined daily at the same hour, and the number of hours of sunshine each day was obtained from the records of the United States Weather Bureau, taken about two hundred yards from the greenhouse. It was thus possible to determine the manner in which these factors affected the use of water by the plants.

The accompanying curve shows how the transpiration rose during the season up to a certain point, when it rapidly decreased. It also shows how fluctuations in the temperature, sunshine, and humidity affected the transpiration in the pots represented. The great falling-off in the transpiration during the two weeks preceding February 20 was doubtless due to snow, which kept the greenhouse covered and cut off a considerable amount of the light.

When the transpiration during 1908–1909 is traced through the season, the following striking results are noted:

During the week from November 21 to 28 there was a substantial increase in transpiration over the previous week in all pots containing 30 per cent water; but in those with 15 per cent water and no fertilizer there was an actual decrease below the previous week, and even where fertilizers were used the increase was not nearly so great in the plants with 15 per cent moisture as in those with 30 per cent.

During the previous week (November 14 to 21) the average temperature was 60.3°. The hours of sunshine during this week were 26.7, while during the following week there were 33.2 hours. The humidity, however, was increased to 68.7 per cent in the second week as compared with 55.2 per cent in the previous week. It appears from the above that the increased temperature and sunshine, even with higher relative humidity, greatly raised the transpiration in pots containing 30 per cent water, while this was not true of the plants grown in the drier soil.

During the week from December 12 to 19 there was a decrease in the transpiration compared with the previous week in the pots with 15 per cent water and without fertilizer. In all other pots there was an increase, it being proportionately greater in the pots with high nitrogen fertilizers. During this week the sunshine decreased to 7.6 hours, as compared with 14.2 hours during the previous week. The relative humidity also decreased from 61.8 to 56.5 per cent. The temperature, however, increased from 59.5° to 62.1°.

During the week from December 26 to January 2 all pots fell off in transpiration as compared with the previous week, the pots with 15

per cent moisture decreasing 25 per cent to 40 per cent, while those with 30 per cent had a decrease of only 3 per cent to 10 per cent. Comparing the two weeks in order, we have the temperature 60.6° and 59.6°, the relative humidity 63.7 and 64, and the total hours of sunshine

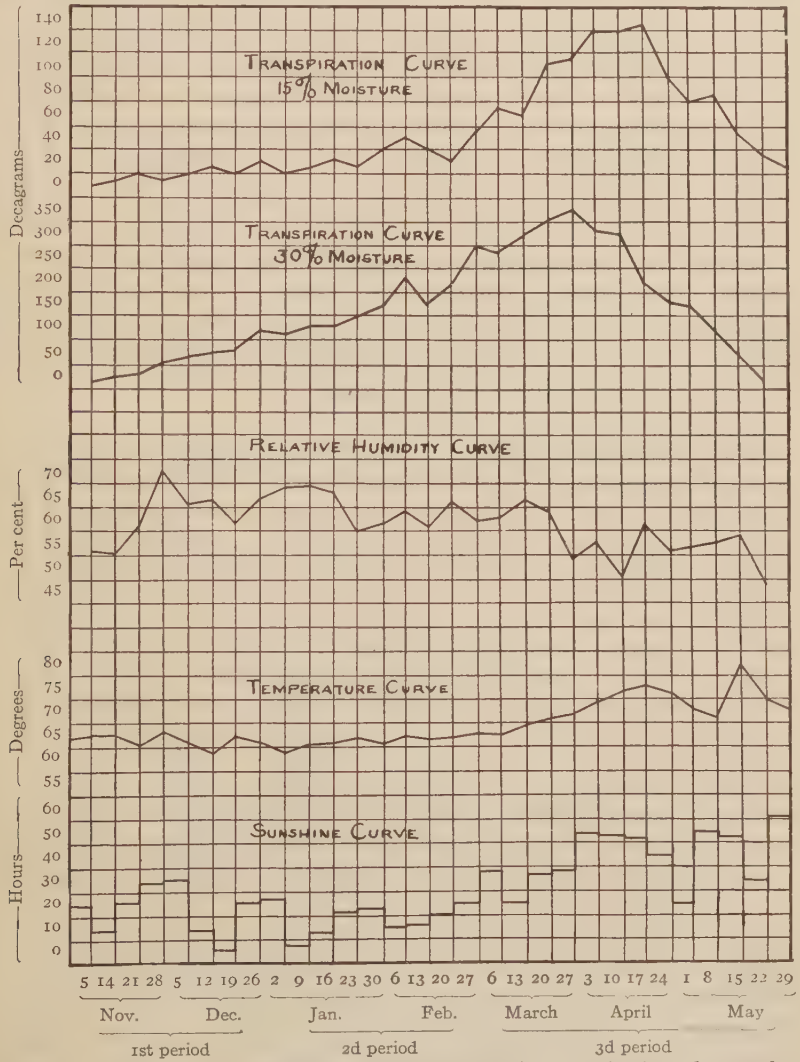

FIG. 108.—*Sunshine, temperature, humidity, and transpiration, by weeks, 1908–1909*

24.3 and 25.9. It is seen from these figures that the factors of temperature, humidity, and sunshine were practically the same during the two weeks. It is difficult, therefore, to account for this falling off in transpiration when we should expect an increase as the plants became larger.

In the two weeks ending on February 20 there was a very marked decrease in transpiration of all treatments as compared with the week ending on February 6. This was the case in all pots. In examining the curve it is found that during these two weeks of lower transpiration the temperature was slightly higher, the sunshine a little more, and the humidity about the same on an average as during the previous week. It was found, however, that most of the sunshine of these two weeks came on a relatively few days, the other days being almost without sunshine. During this time the greenhouse was covered with snow, which was probably responsible for the great lowering in transpiration as has already been suggested.

EFFECTS ON THE COMPOSITION OF WHEAT

Percentage and total weight of nitrogen

Nitrogen was determined in all plants harvested. The method used was the Gunning modification of the Kjeldahl method, as outlined in the methods of the Association of Official Agricultural Chemists. The results are summarized in the tables that follow.

TABLE 42. EFFECT OF DIFFERENT SOIL MOISTURE CONTENTS ON THE PERCENTAGE AND TOTAL WEIGHT OF NITROGEN IN WHEAT. NO FERTILIZER. 1909–1910

Soil moisture (percentage)	Number of pots	Percentage of nitrogen			Total weight of nitrogen per pot (in grams)		
		In grain	In straw	In grain and straw	In grain	In straw	In grain and straw
11	2	3.24	.69	1.38	.132	.077	.209
13	2	3.13	.49	1.28	.155	.064	.219
20	2	2.51	.42	1.04	.225	.088	.313
25	2	2.30	.34	.94	.236	.084	.320
37½	2	2.26	.40	.93	.309	.138	.447
45	2	2.39	.40	.90	.219	.106	.325

First, considering the composition of the grain, it is seen that the highest percentage of nitrogen was produced on the driest soil and that the percentage decreased as the moisture increased up to 37½ per cent; but that the grain on the excessively wet soil had a slightly higher percentage of nitrogen than that on the moderately wet soil. The percentage of nitrogen in the grain from the very dry soil was more than 35 per cent greater than that in the grain from the wet soil. The percentage of nitrogen in the straw ran in about the same way as that in the grain, except that the lowest was in the straw produced with 25 per cent moisture.

The straw with $37\frac{1}{2}$ per cent and that with 45 per cent moisture had the same percentage of nitrogen. The straw and the grain together, however, showed a lower nitrogen content where there was 45 per cent soil moisture, notwithstanding the fact that neither the straw nor the grain alone had a lower percentage. The explanation of this seeming paradox is found in the fact that there was proportionately more of the straw in one case than in the other, and its small amount of nitrogen reduced the general average.

It has been a common observation that a higher percentage of nitrogen is produced under drier conditions, but to have the nitrogen content rise when the soil moisture is raised above a certain limit is something entirely new to the author. The explanation that is usually given in the literature of the subject, for high nitrogen accompanying dry conditions, is that there is a hastened maturity and an arrested development. This theory would not be borne out by the data presented here, since, as was shown in Table 20, the period of growth was ten days longer in the plants producing the highest percentage of nitrogen in the grain than in those producing the lowest percentage. Also the length of the growing period, as well as the percentage of nitrogen, was greater in plants with 45 per cent water than in those with $37\frac{1}{2}$ per cent. As previously pointed out, the grain on the dry soil was plump and heavy, so that its high nitrogen could not be due to a shrinking of the kernels. The kernels raised with 45 per cent moisture were somewhat shrunken, however.

When the total weight of nitrogen produced in a pot is considered, the plants with $37\frac{1}{2}$ per cent moisture produced the most, notwithstanding the fact that their percentage was so low. This, of course, was due to the comparatively large crop.

TABLE 43. EFFECT OF HIGH AND OF LOW MOISTURE DURING DIFFERENT PERIODS OF GROWTH ON THE PERCENTAGE AND TOTAL WEIGHT OF NITROGEN IN WHEAT. AVERAGE FOR ALL FERTILIZER TREATMENTS. RESULTS FOR TWO YEARS

Percentage of soil moisture			Number of pots	Percentage of nitrogen								Total weight of nitrogen per pot (in grams)							
				In grain		In straw		In grain and straw		In roots		In grain		In straw		In grain and straw		In roots	
First stage	Second stage	Third stage		1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910	1908–1909		1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	
30	30	30	6	2.62	2.05	.40	.36	.85	.82	.99		.261	.390	.152	.163	.413	.553	.054	
30	30	15	6	2.82	2.19	.48	.41	.97	.90	1.20		.241	.377	.154	.181	.395	.558	.081	
30	15	15	6	2.98	2.31	.56	.44	1.02	.98	1.36		.196	.365	.159	.169	.355	.534	.083	
15	15	15	6	3.24	2.42	.60	.42	1.10	1.00	1.27		.128	.253	.094	.113	.222	.366	.076	
15	15	30	6	3.24	2.52	.66	.45	1.30	1.11	1.30		.235	.354	.137	.135	.372	.489	.077	
15	30	15	6	2.96	2.21	.49	.39	1.04	.93	1.24		.219	.334	.124	.147	.343	.481	.108	

The crop produced with 30 per cent moisture during all three periods contained the lowest percentage of nitrogen in the total plant as well as in each part. The crop richest in nitrogen received 15 per cent moisture during the first two periods and 30 per cent during the third period. This was true of both grain and straw during both seasons. It will be noticed that the stage when the moisture was changed had a considerable influence. For example, in the plants receiving high moisture during but one period the percentage of nitrogen was much less where the high moisture was given during the first or the second period than where it was given during the third. The percentage of nitrogen in the roots varied similarly to that in the tops, but was different in some respects.

The total quantity of nitrogen produced per pot was also considerably affected by the changes in moisture, but the chief thing that affected it was the size of crop. Thus the treatment that gave the lowest percentages gave the largest total yield of nitrogen. Where the moisture was raised during but one period, the total nitrogen was decidedly greater than where the soil remained dry all the time.

TABLE 44. EFFECT OF FERTILIZERS ON THE PERCENTAGE AND TOTAL WEIGHT OF NITROGEN PRODUCED PER POT. AVERAGE FOR ALL MOISTURE TREATMENTS. RESULTS FOR TWO YEARS

Fertilizer	Number of pots	Percentage of nitrogen							Total weight of nitrogen per pot (in grams)						
		In grain		In straw		In grain and straw		In roots	In grain		In straw		In grain and straw		In roots
		1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1908–1909	1909–1910	1908–1909	1909–1910	1908–1909	1909–1910	1908–1909
None	12	2.95	2.21	.47	.37	1.05	.91	1.17	.166	.218	.096	.089	.262	.307	.070
Complete	12	2.85	2.14	.50	.34	.97	.87	1.17	.227	.335	.135	.130	.362	.465	.077
High nitrogen	12	3.13	2.47	.63	.52	1.14	1.11	1.33	.248	.452	.179	.236	.427	.688	.091

In practically every case the percentage of nitrogen was higher in the plants on the unfertilized soil than on that receiving the balanced complete fertilizer. On the soil with high nitrogen fertilizer, however, the nitrogen content of the crop was very much higher than with either of the other treatments.

When total weight of nitrogen produced per pot is considered, the unfertilized soil had the least. This was because of the considerably smaller crop.

Composition at different stages of growth

In 1908–1909 plants were harvested at the boot and bloom stages, as well as at maturity, and were analyzed, with the results given in Table 45:

TABLE 45. NITROGEN IN WHEAT AT VARIOUS STAGES OF GROWTH WITH DIFFERENT TREATMENTS. 1908–1909

Fertilizer	Soil moisture (percentage)	Percentage of nitrogen						Total weight of nitrogen in two pots (in grams)					
		In tops			In roots			Tops			Roots		
		Boot	Bloom	Maturity	Boot	Bloom	Maturity	Boot	Bloom	Maturity	Boot	Bloom	Maturity
None.....	30	1.23	.94	.83	1.36	1.23	.96	.434	.472	.619	.214	.132	.089
None.....	15	1.62	1.32	1.25	1.68	1.59	1.36	.247	.245	.366	.168	.134	.130
Complete....	30	1.31	.88	.77	1.20	1.15	.98	.597	.668	.793	.273	.164	.115
Complete....	15	1.62	1.17	.96	1.50	1.35	1.30	.450	.465	.514	.312	.167	.171
High nitrogen	30	2.30	1.30	.95	1.98	1.26	1.03	.912	.986	1.068	.277	.159	.117
High nitrogen	15	1.85	1.52	1.20	1.62	1.58	1.16	.490	.497	.455	.292	.180	.152

The table brings out clearly the well-known fact that the percentage of nitrogen is higher during early than during late periods of growth. This is true for both the tops and the roots. The soils with low moisture always produced a higher percentage of nitrogen except in the case of the high nitrogen fertilizer at the boot stage, when there was a higher percentage of nitrogen accompanying the high moisture. This may have been due to the fact that the high nitrogen fertilizer did not become accessible to the plants with low moisture as early as it did to those with high moisture.

When the results for total nitrogen are examined, some very interesting relations are seen. In the roots the greatest total weight of nitrogen was present at the boot stage, and it had decreased decidedly by maturity. There was always a greater decrease in the wet soil than in dry.

Most of the nitrogen in the tops had been taken up by the boot stage, but there was usually a little increase up to maturity. With the high nitrogen fertilizer and low soil moisture, the greatest amount taken up was by the bloom stage and there was a decrease between that stage and maturity. It is a striking fact that on the drier soils a relatively larger amount of the nitrogen was taken up by the boot stage than on the wet soils.

Ash constituents

A determination was not made of the ash constituents of all treatments, and therefore no tables will be presented. The following determinations, however, were made in the wheat straw raised with high nitrogen fertilizer: crude ash, calcium, magnesium, potassium, and phosphoric acid. Since the work was not complete, no definite conclusions can be drawn, but sufficient work was done to bring out a few interesting points. The percentages of crude ash, calcium, magnesium, potassium, and phosphoric acid were all lower in straw grown with high moisture than in that grown

with low moisture. Where there was low moisture during one or two stages, the percentage of the ash constituents was also higher than where the high moisture was maintained throughout.

With all the constituents, and with phosphoric acid and potassium in particular, low moisture during the first period of growth increased the percentage of ash much more than low moisture during any other period.

SUMMARY

1. Experiments on the relation of soil moisture and fertilizers to soil conditions and to the growth of plants are of great interest to the investigator as well as to the tiller of the soil.

2. The important literature on this subject is reviewed topically.

3. Experiments were conducted in the greenhouse and in the laboratory, with wheat plants grown in pots containing soil with different moisture and fertilizer treatments. Studies were also made of certain properties of the cropped and the uncropped soils standing for long periods under the conditions named.

4. A study of the volume weight showed that the cropped soil was more compact than the uncropped, and the volume of the soil decreased as the moisture that it contained increased. Fertilized soils with crops were more compact than unfertilized soils.

5. In the cropped soil the particles were more flocculated than in the uncropped; and the flocculation was greater with a medium degree of soil moisture than with a very large or a very small degree, the least flocculation going with the very wet soil. Flocculation was increased by fertilizers, especially those that contained little sodium nitrate.

6. Nitrates were always higher in an uncropped than in a cropped soil, and were higher with 30 per cent moisture than in a drier or a wetter soil. Where the soil was kept saturated with moisture, practically no nitrates were present, denitrification having taken place. The nitrates were higher in soils to which nitrate fertilizers had been added.

7. The nitrite content of the soils was always low, but was higher on the uncropped soil than on the cropped and was higher where high nitrogen fertilizers had been added.

8. Unlike nitrates and nitrites, the ammonia was always higher in cropped than in uncropped soils. The amount of ammonia was never great and was not much affected by the soil moisture. It was highest where a high nitrogen fertilizer was used.

9. The total water-soluble salts were not taken up by plants as rapidly as were the nitrates, so that the ratio of soluble salts to nitrates was always higher in cropped than in uncropped soil. Fertilizers previously applied increased the total soluble salts.

10. No definite conclusions could be drawn regarding the number of bacteria in the soil. However, the number was usually greater with 15 per cent than with 30 per cent moisture. It was also slightly greater in unfertilized than in fertilized soil.

11. The easily soluble phosphoric acid was always higher in the uncropped than in the cropped soil, and higher in the fertilized than in the unfertilized soil. It varied with the soil moisture, but the variation was not regular.

12. The length of the various periods of growth was greatly affected by soil moisture and fertilizers. Wheat matured sixteen days earlier with 20 per cent moisture than with either 11 per cent or 45 per cent. The period at which high moisture was applied had an effect on the time of ripening. A well-balanced fertilizer caused an earlier maturity than one with high nitrogen or no fertilizer.

13. Tillering was promoted by high moisture and by fertilizers.

14. Plants were able to stand excessive moisture better when young than when older.

15. The attacks of mildew were severest on plants growing with high moisture and a high nitrogen fertilizer.

16. The number of nodes per culm was least with a medium, and most with the very high, soil moisture. The length of culms and of heads increased with the moisture up to $37\frac{1}{2}$ per cent, after which both decreased. The heads were proportionately longer in the dry than in the wet soil. The quantity of moisture during the early growth, more than at any other time, determined the head as well as the culm length. Fertilizers increased the number of nodes per culm, as well as the length of culm and of head.

17. The number of kernels of wheat per pot increased with the fertilizers. It also increased with the soil moisture up to $37\frac{1}{2}$ per cent, above which point it decreased. The number of kernels per head was greatest on the soil with a medium amount of moisture, but the weight of one hundred kernels was greatest on the very dry soil and least on the very wet. The kernels raised on the wet soils were soft and starchy in appearance.

18. Proportionately more of the dry matter in wheat had been produced by the boot stage in the dry soil than in the wet. After the boot stage the weight of roots, which could be washed out, decreased to maturity.

19. The greatest quantity of both grain and straw was produced with $37\frac{1}{2}$ per cent moisture, but the relative amount of grain was greatest with a medium low moisture (20 per cent). The period at which moisture was high or low greatly affected the ratio of straw to grain, there being proportionately more grain when the soil moisture was low during early

stages. Fertilizers increased the yield of both grain and straw, but especially of straw.

20. The total transpiration was greatly affected by fertilizers and soil moisture, and the greatest transpiration was in the plants producing the most dry matter. In relation to dry matter produced, water was transpired most economically with a medium degree of soil moisture, but the economy was greater on a very dry than on a very wet soil. Water was used most economically in the production of grain when the soil was kept comparatively dry up to the boot stage, and then kept wet until maturity. The total dry matter in the plant as a whole, however, was produced most economically when the soil was kept wet until the five-leaf stage, and drier from that stage to maturity. The manner in which fertilizers increased the economy of water transpired was dependent on the efficiency of the fertilizers and on the moisture conditions of the soil. The season and the variety of wheat affected the relation between transpiration and dry matter.

21. The relation between the amount of water transpired by the different treatments did not remain the same during all periods of growth. The manner in which transpiration responded to heat, sunshine, and humidity of the air depended, to an extent, on the soil treatment.

22. The percentage of nitrogen in both grain and straw was highest on the driest soil, and gradually decreased as the moisture increased up to $37\frac{1}{2}$ per cent; but as the soil approached saturation the percentage of nitrogen in the grain slightly increased. The grain with the highest percentage of nitrogen was plump and had a flinty appearance. The highest percentage of nitrogen did not go with the earliest maturity.

23. The period of growth at which high or low moisture was given greatly affected the composition of wheat. The condition that gave the highest percentage of nitrogen both in the grain and straw was where the moisture was low up to the boot stage, and high from that stage to maturity. It will be remembered that this was also the treatment that used water most economically in producing grain. The lowest nitrogen was found where the moisture was high during all periods.

24. The high nitrogen fertilizer always increased the nitrogen content of the crop. While the percentage of nitrogen was not so great in the crop produced with complete fertilizer as with no fertilizer, yet the total weight of nitrogen was much greater, due to the larger crop.

25. The percentage of nitrogen in the crop rapidly decreased from the boot stage to maturity, the decrease being greater in the tops than in the roots, and greater in the crops on the wet soil than in those on the dry. The total weight of nitrogen in the roots was greatest at the boot stage and decreased to maturity. In the tops, however, there was usually

a slight increase in total nitrogen after the boot stage. In the dry soil a greater proportion of the total nitrogen had been taken up by the boot stage than had been taken up in the wet soil.

26. The percentage of crude ash, calcium, magnesium, potassium, and phosphoric acid was lower in wheat straw grown with high moisture than in that grown with low moisture.

27. These experiments bring out clearly the facts that the moisture relations of plants are greatly affected by the fertility of the soil, and that the effect of a fertilizer is dependent on the amount of soil moisture. They emphasize also the fact that fertilizer experiments, in order to be of value, must be made under widely varying moisture conditions; and that experiments with the use of moisture by plants, in order to be conclusive, must include a number of fertility conditions.

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